FORESTRY 063

# Proceedings of the CARNATION CREEK Herbicide Workshop

ISSN 0835 0752

MARCH 1989

ECONOMIC & REGIONAL DEVELOPMENT AGREEMENT

Canada

BC

89-03676/

BC
F6
C
F1072 M63
1989

# Proceedings of the Carnation Creek Herbicide Workshop

December 7 - 10, 1987

**P.E. Reynolds, Ed.**

Forest Pest Management Institute
Forestry Canada
1219 Queen St. E.
Sault Ste. Marie, Ontario
P6A 5M7

**March 1989**

ECONOMIC & REGIONAL DEVELOPMENT AGREEMENT

Canada

BC

Partial funding for the research project and the cost of printing this publication was provided by the Canada-British Columbia Forest Resource Development Agreement - a five year (1985-90) $300 million program cost-shared equally by the federal and provincial governments. Additional funding was provided by Monsanto Canada.

**Canadian Cataloguing in Publication Data**

Carnation Creek Herbicide Workshop (1987 : Nanaimo, B.C.).
Proceedings of the Carnation Creek Herbicide Workshop

(FRDA Report, ISSN 0835–0752 ; 063)

Issued under Forest Resource Development Agreement.
Co-published by B.C. Ministry of Forests.
"Canada/BC Economic & Regional Development Agreement".
ISBN 0–7726–0917–9

1. Glyphosate. 2. Herbicides – Environmental aspects – British Columbia – Carnation Creek. 3. Herbicides – British Columbia – Carnation Creek – Toxicology. I. Reynolds, P.E. (Phillip E.), 1947– . II. Canada. Forestry Canada. III. British Columbia. Ministry of Forests. IV. Forest Resource Development Agreement (Canada) V. Canada/BC Economic & Regional Agreement. VI. Title. VII. Series

SB952.G58C37 1989 632'.954 C89–092067–2

© 1989 Government of Canada,
Province of British Columbia

This is a joint publication of Forestry Canada and the British Columbia Ministry of Forests.

Produced and distributed by the Ministry of Forests, Research Branch.

For additional copies and/or further information about the Canada-British Columbia Forest Resource Development Agreement, contact:

Forestry Canada
Pacific Forestry Centre
506 West Burnside Road
Victoria, B.C. V8Z 1M5
(604) 388-0600

or

B.C. Ministry of Forests
Research Branch
31 Bastion Square
Victoria, B.C. V8W 3E7
(604) 387-6719

# FOREWORD

The Carnation Creek Herbicide Workshop was held on December 7-10, 1987 in Nanaimo, B.C. Over 150 people attended the workshop, which featured two days of oral presentations and a wrap-up one day discussion session. At the discussion session, workshop attendees divided up into various working groups to address special topics arising from the oral presentations. The workshop was the third Carnation Creek Workshop to be held.

The objective of the present workshop was to facilitate discussion of ROUNDUP research conducted at Carnation Creek, and elsewhere within B.C., by operational and regulatory personnel. The wrap-up discussion sessions allowed environmental and fisheries regulatory personnel to interact with operational foresters in addressing problems and opportunities of mutual interest. Both groups are responsible for managing or regulating forest vegetation control treatments within coastal B.C. The discussion groups attempted to evaluate what is currently known based upon research presented at the workshop, what sorts of regulatory or operational policy changes are warranted based upon the conclusions of this research, and what additonal research would be desirable based upon data gaps indentified by the participants. Publication of the proceedings was delayed until after the workshop to allow for inclusion of these important deliberations.

Special thanks are extended to the many people who contributed to the organization and running of the workshop and to the countless hours of editing, word processing, and graphic art necessary to produce this proceedings in a final camera-ready version. Kathy Banky, Dan Lousier and Rick Ellis were responsible for organizing the workshop and for transcribing the deliberations of the discussion groups. Following the workshop, FPMI's word processing unit worked for nearly 15 months to produce this proceedings; I am grateful to Joanne Theriault, Donna Weeks, Judy Novick and Edna Morningstar for their untiring devotion to this project. The drawings in the various FPMI papers are the work of Sandra Mantulak. I reserve special praise and thanks for Karen Jamieson, FPMI's Scientific Editor, without whose able stewardship this proceedings would not have been possible. While Karen was away on maternity leave, Fiona Ortiz worked closely with me as Acting Scientific Editor. Finally, I thank Steve Chatwin for his assistance in preparing to go to press with this proceedings.

Often research papers do not bear the names of those who worked very hard to collect the data. Results presented in this proceedings would not have been possible without the efforts of Bruce Andersen, Jim Beveridge, Brent Birkedal, Tom Brown, T. Buscarini, A. Carter, Liesbet Croockewit, Dana Dekoven, Wayne Enlow, W.W. Kay, Herb Klassen, P. Kluckner, A. Langston, Dick Leahy, G. Lough, Linda MacDonald, Virve Manniste-Squire, Kevin McCullough, P.C.K. Pang, R. Rowswell, Bozena Staznik, K. Stephens, John Studens, Dal Travnick, Min Tsze, and Ann van Niekerk.

For me, completion of this project is a dream come true. Many thought the project was worth doing, but few felt it could be done. This proceedings is a tribute to those who believe dreams can come true. Two individuals deserve special mention and recognition for their efforts. Henry Benskin shared the dream from inception; I shall always be grateful for his untiring devotion to the success of this project. Charlie Scrivener, one of the founding fathers and guiding lights of the Carnation Creek research, has been a true delight and inspiration to work with. I am honoured to have had the opportunity and the privilege to work with Charlie.

Funding for a significant portion of the research, for the workshop and the proceedings was provided by the Canada-British Columbia Forest Resource Development Agreement (FRDA).

Phillip Reynolds
Editor and Coordinator of Herbicide Research

## TABLE OF CONTENTS

Page

FOREWORD . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . iii

**SESSION I: Introduction to the Workshop by a panel representing a variety of interests.**

Carnation Creek herbicide workshop. Opening remarks.
L. Carlson . . . . . . . . . . . . . . . . . . . . . . . . . 1

Introduction: Cooperation in resource management.
W.W. Bourgeois . . . . . . . . . . . . . . . . . . . . . . . 4

Introduction: Issues and concerns relating to the use of herbicides
P. Akhurst . . . . . . . . . . . . . . . . . . . . . . . . . 6

Introductory paper: Fisheries issues.
S. Samis . . . . . . . . . . . . . . . . . . . . . . . . . . 12

**SESSION II: Chairman, Errol Caldwell, Program Director, Forest Pest Management Institute**

An overview of Carnation Creek herbicide study: historical perspective, experimental protocols and spray operations.
P.E. Reynolds, J.C. Scrivener, L.B. Holtby, P.D. Kingsbury . . 15

Carnation Creek flood hydrology September 1984 to September 1985.
E. Hetherington . . . . . . . . . . . . . . . . . . . . . . 27

Fate of glyphosate in a Canadian forest stream ecosystem.
J.C. Feng, D.G. Thompson, P.E. Reynolds . . . . . . . . . . . 45

Persistence and dissipation of glyphosate in foliage and soils of a Canadian coastal forest watershed.
J.C. Feng, D.G. Thompson . . . . . . . . . . . . . . . . . . 65

Off-target deposit measurements and buffer zones required around water for various aerial applications of glyphosate.
N. Payne, J.C. Feng, P.E. Reynolds . . . . . . . . . . . . . 88

**SESSION III: Chairman, Jack Dryburgh, MacMillan Bloedel Ltd.**

Development of non-commercial vegetation following clearcutting and clearcutting-plus-slashburning, and some biogeochemical effects of herbicidal control of this vegetation.
J.P. Kimmins, K.M. Tsze, R.E. Bigley . . . . . . . . . . . . 110

Effect of glyphosate (ROUNDUP) on biological activity of two forest soils.
C.M. Preston, J.A. Trofymow . . . . . . . . . . . . . . . . 122

## TABLE OF CONTENTS (cont'd)

Page

**SESSION III:** (cont'd)

Three-year herbicide efficacy, crop tolerance and crop growth response results for a 1984 glyphosate conifer release trial at Carnation Creek, British Columbia.
P.E. Reynolds, D.G. Pitt, R. Whitehead, K. King . . . . . . . 141

Comparison of the effects of chemical (glyphosate) and manual conifer release on conifer seedling physiology and growth on Vedder Mountain, British Columbia.
J. Karakatsoulis, J.P. Kimmins, R.E. Bigley . . . . . . . . . 168

Crop tolerance of three west coast conifer species to glyphosate.
R. Prasad . . . . . . . . . . . . . . . . . . . . . . . . . 189

**SESSION IV: Chairman, Ian Williams, Program Director, Pacific Biological Station**

Comparative changes in concentration of dissolved ions in the stream following logging, slash burning, and herbicide application (glyphosate) at Carnation Creek, British Columbia.
J.C. Scrivener . . . . . . . . . . . . . . . . . . . . . . . 197

Changes in the temperature regime of a valley-bottom tributary of Carnation Creek, British Columbia, oversprayed with the herbicide ROUNDUP (glyphosate).
L.B. Holtby . . . . . . . . . . . . . . . . . . . . . . . . 212

Effects of the herbicide ROUNDUP (glyphosate) on periphyton in Carnation Creek, British Columbia.
L.B. Holtby, S.J. Baillie . . . . . . . . . . . . . . . . . 224

Litter-fall and detrital decomposition rates in a tributary of Carnation Creek, British Columbia, oversprayed with the herbicide ROUNDUP (glyphosate).
L.B. Holtby, S.J. Baillie . . . . . . . . . . . . . . . . . 232

Drift of aquatic invertebrates in a glyphosate contaminated watershed.
D.P. Kreutzweiser, P.D. Kingsbury . . . . . . . . . . . . . 250

Salmonid toxicity studies with ROUNDUP.
P.M. Chapman . . . . . . . . . . . . . . . . . . . . . . . . 257

Changes in the invertebrate populations of the main stream and back channels of Carnation Creek, British Columbia following spraying with the herbicide ROUNDUP (glyphosate)
J.C. Scrivener, S. Carruthers . . . . . . . . . . . . . . . 263

## TABLE OF CONTENTS (cont'd)

Page

**SESSION IV: (cont'd)**

Effects of the herbicide ROUNDUP on coho salmon fingerlings in an oversprayed tributary of Carnation Creek, British Columbia.
L.B. Holtby, S.J. Baillie . . . . . . . . . . . . . . . . . . . . 273

**SESSION V: PERSPECTIVES**

Perspective: Risk management and the public.
J. Henigman . . . . . . . . . . . . . . . . . . . . . . . . . 286

Perspective: The effects of forestry use of glyphosate on human health.
D. Bowering . . . . . . . . . . . . . . . . . . . . . . . . . 288

**SESSION VI: DISCUSSION GROUP PRESENTATIONS**

Discussion groups 1 & 2 - Soils
Group leaders - Mark Walmsley and Terry Lewis . . . . . . . . . 294

Discussion group 3 - Water: herbicide characteristics and water quality
Group leader - Doug Wilson . . . . . . . . . . . . . . . . . . 295

Discussion group 4 - Water
Group leader - Dave Wilford . . . . . . . . . . . . . . . . . . 297

Discussion group 5 - Aquatic organisms
Group leader - Steve Samis . . . . . . . . . . . . . . . . . . 300

Discussion group 6 - Aquatic orgamisms
Group leader - Vince Poulin . . . . . . . . . . . . . . . . . . 301

Discussion group 7 - Wildlife
Group leader - Harold Armleder . . . . . . . . . . . . . . . . 303

Discussion group 8 - Wildlife
Group leader - Sylvia von Schuckmann . . . . . . . . . . . . . 305

Discussion group 9 - Forestry
Group leader - Dick Kosick . . . . . . . . . . . . . . . . . . 307

Discussion group 10 - Forestry
Group leader - Wayne Coombs . . . . . . . . . . . . . . . . . . 309

Discussion group 11 - Spray technology
Group leader - Dan Cronin . . . . . . . . . . . . . . . . . . . 311

# TABLE OF CONTENTS (concl.)

Page

SESSION VI: (cont'd)

Discussion group 12 - Spray technology
Group leader - John Henigman . . . . . . . . . . . . . . . . . . . 312

Discussion group 13 - Social concerns
Group leader - David Bowering . . . . . . . . . . . . . . . . . . 313

Discussion group 14 - Social concerns
Group leader - Paul Pashnik . . . . . . . . . . . . . . . . . . . 315

SESSION VII: WRAP-UP SESSION

Conference summation: the Carnation Creek herbicide test workshop.
M. Halleran . . . . . . . . . . . . . . . . . . . . . . . . . . 318

A summary of Carnation Creek herbicide study results.
P.E. Reynolds, J.C. Scrivener, L.B. Holtby, P.D. Kingsbury . . 322

Appendices
Symposium attendees . . . . . . . . . . . . . . . . . . . . . . 335

# CARNATION CREEK HERBICIDE WORKSHOP

## OPENING REMARKS

Les Carlson
Director, Research and Development
Canadian Forestry Service
Ottawa, Ontario
K1A 1G5

I am happy to be here with you this morning, although I must confess that at times I wasn't sure that I would make it--between getting travel authorization and then working around the Air Canada strike. It is my pleasure to be with a group of interesting people working on an important forestry and environmental problem such as the use of herbicides in the forest.

This morning, in addition to a little commercial background on the CFS, I would like to cover three other specific points regarding herbicide research: a) the problem and the initial approaches by the CFS; b) a little about our overall approach to research in this area; and c) herbicide research in context of the National Forest Sector Strategy.

**This workshop represents a significant effort and contribution by all of the agencies involved, particularly the CFS and DFO. Equally recognized are the contributions of the B.C. Ministry of Forests and Lands, the B.C. Ministry of Environment and Parks, and the forest industries in the province, in particular MacMillan Bloedel Limited. While the workshop is focussed on the use of glyphosate, its approach to the overall problem involved in the use of herbicides in our forests will be useful for future research programs.**

First of all, for those of you who don't know who we are, the Canadian Forestry Service is part of Agriculture Canada. We hold a unique position within the Department in that we are represented by a Minister of State (Forestry and Mines) in the Government's Cabinet. This is an administrative arrangement that allows us to develop and carry out our own programs without having the political domination of Agriculture, yet allows us to use their political strength in support of our programs. Like all marriages, it takes a lot of effort to make the arrangement work.

The Service will be 90 years old in two years and for most of that time it has been specifically oriented toward research. We have, however, at several different times in our existence, been involved in the delivery of joint federal/provincial forestry agreements. We are in that mode at the present time. In fact, the Canada/British Columbia forestry agreement is involved in funding this workshop.

The scope of our research, for example, ranges from this project on application and environmental affects of glyphosate to micropropagation of conifers to remote sensing technology. And like K-Tel records, many, many more activities in support of forestry and the forest interests of the people of Canada.

The second point I want to make is that we got into herbicide research because there was a need for the forest sector to have a variety of weed control options if they were going to be able to successfully put back those trees that they had taken in the harvesting process. We were aware of the need before, but it wasn't until 1980 that the issue became more pressing. The CFS, while we were with federal Department of the Environment, in cooperation with Agriculture Canada and other federal agencies involved in the registration of pesticides, then organized a steering committee to review the work needed to complete the registration of several herbicides, i.e. glyphosate, hexazinone, and others. The Forest Pest Management Institute has been the CFS lead in the federal registration process for forest pesticides and therefore plays an important role in all pesticide research in forestry across Canada.

Now that you are aware of how we got into programs such as the Carnation Creek study with glyphosate, my third point is that you should be aware of the extent of CFS involvement in herbicide research. The Forest Pest Management Institute established a series of studies across the country that were designed to answer some of the more important concerns raised with the use of herbicides. Those concerns have been articulated very well by knowledgeable biologists, environmentalists, citizens and politicians.

Our research programs involving herbicides have been limited to the Institute, but have had a definite regional orientation. There has been work in Newfoundland, Ontario, the prairies and here in British Columbia.

The CFS research program, recognizing the concerns for the environment, is focussed toward developing ecologically sound forest practices using herbicides and alternatives to herbicides in forest weed control. We have done this through various programs in some of our regional centres.

More specifically, here in B.C., the Pacific Forestry Centre has six scientists working on topics related to weed control such as weed autecology, as related to site preparation methods, and manual weed control methods (including the recent demonstration to contractors near Nelson on the use of brush saws). Included in this group are two researchers the Centre has brought in from other parts of the Canadian Forestry Service to work on the biocontrol of weeds using plant pathogens. This is the first effort of its kind in forestry in Canada, although work on biological control of weeds has been going on for some time in agriculture using insects and pathogens.

I want to issue a warning here. Biological controls are to be considered the ultimate in our fight against pests of all kinds. With insect control we have had some very good successes, but we face some extreme difficulties with weed control. It is high risk research, yet we intend to move forward in this area. In the meantime it will be necessary to have other tools in our hands for the management of the forests. Therefore, we will continue to develop methods that use safe chemicals and that allow us to safely apply effective chemicals.

Having seen how we got involved in the problem and some of the responses the CFS has taken, I would like to take up my fourth point of how these actions fit in with the context of the National Forest Sector Strategy for Canada.

Many of you may be aware that during the past two years the forest sector in Canada has been meeting in a series of four forums designed to thrash out the sector's problems. This series culminated last July in a meeting in Saint John, New Brunswick that developed a National Forest Sector Strategy for Canada. The strategy was approved by the Canadian Council of Forest Ministers in September. The full text of the strategy can be found in the October 1987 issue of The Forestry Chronicle.

Protection of the forests and reforestation were high on the list of priorities in the strategy. Two recommendations have to be considered in context of the program of research on herbicides and weed control.

Recommendation #9 reads: "It is recommended that all elements of the forest sector recognize that pesticides are among the legitimate means of effective forest management in specific areas, that their use continue to be regulated; and [that the forest sector]

- ensure that all pest management operations are ecologically and economically justified;

- encourage development and use of effective alternative methods of pest control, including integrated pest management;
- accelerate research into the environmental effects of pesticides; and
- ensure that the process for registration of pesticides for forest use is not cost prohibitive and is open to public scrutiny."

The second recommendation I want to bring to your attention is Recommendation #7 which reads: "It is recommended that foresters and wildlife managers cooperate in the review and development of forest, fisheries, wildlife, and integrated management." I also read this to include fisheries managers.

As we go through the next few days we should keep the spirit of these recommendations in mind. It is the latter that calls us to muster our resolve to work collectively and I see in this workshop a real opportunity to do so.

Thank you for listening and I hope you have a very profitable meeting.

# INTRODUCTION: COOPERATION IN RESOURCE MANAGEMENT

Bill Bourgeois
MacMillan Bloedel Ltd.
65 Front St.
Nanaimo, B.C.
V9R 5H9

Today I would like to talk to you briefly about cooperation in resource management. In the late 1970s the attitude for cooperation began to build momentum in resource management in coastal British Columbia. The economic downturn accentuated the need for this approach. All organizations and agencies found themselves in the position of not having or expecting to have the resources necessary to conduct priority activities. It was quickly accepted by many people that we needed to work together. Moving in this direction has not been without its problems. An example of this was the coastal fisheries/forestry guidelines. Fortunately, we have benefited from this experience with acceptance of the guidelines as a final result.

The guidelines contain a statement agreed to by all agencies and COFI that should serve as a basis for the approach to fisheries and forestry management. The statement is: "the objective of the coastal fisheries guidelines is to maximize the net benefits of the combined fisheries and forestry resources while minimizing time and cost." To satisfy this objective a cooperative approach is essential.

The economic and social world we live in today demands we manage our natural resources in truly an integrated manner. We cannot tolerate unjustified single use management. I recognize there are instances where the only known way to satisfy the guidelines objective is for single use management. However, we must strive to obtain information and tools that will keep these situations at a minimum. It is in this area where the work being discussed over the next three days is a prime example.

The challenge before you and other research and operations people is to conduct this work in a cooperative way. If we are to be successful in meeting this challenge, we cannot tolerate people or organizations that are not willing to work cooperatively towards the objectives of integrated resource management. We all know there are insufficient people and dollar resources available to conduct all the needed activities. If our objective is to use the available resources efficiently and effectively, a cooperative approach is the only way. It's easy to say "let's do the project or activity cooperatively"; it's more difficult to actually do it. It requires the individuals have skills to work as a team. It is also necessary that all parties agree on a common goal and be willing to deal with the differences of opinion in an objective and up front manner. The approach is not easy. We will all have to work hard at developing the cooperative approach.

The Carnation Creek program is a good example of a successful cooperative approach. I think all participants have gained over the years from this synergy. The herbicide project that you will be discussing is a challenge to all of you to continue the positive attitude and approach taken in the Carnation Creek program. We all know the herbicide issue is emotional and politically sensitive. This is an added challenge to the cooperative approach. How do we deal with the forestry concerns of productivity declines due to lack of vegetation control, costs of leaving pesticide free zones, and approval for use of safe and effective chemicals? At the same time we have to consider the fisheries concerns of toxicity of chemicals to fish, accumulation of chemicals in the fish eaten by humans, and removal of required streamside vegetation. In addition we have to consider the political and emotional concerns of "chemicals are bad" and the pollution of domestic water supplies. Although it is not easy, we must insist on a cooperative approach to both research and operations activities involving the herbicide issue.

In summary, I would like to leave you with the following comments: we must manage resources in an integrated manner; our objective must be to maximize net benefits of the combined fisheries and forestry resources; available people and dollar resources are and will continue to be insufficient; the cooperative approach and attitude is essential if we are to use these resources effectively and efficiently. There are great challenges confronting us in conducting our business in this manner, especially in the areas such as herbicides. In the 1980s and 90s, there is no room in resource management for people or organizations that do not accept the co-operative approach. I leave you with this challenge and hope that the next three days assist you in meeting it.

# INTRODUCTION: ISSUES AND CONCERNS RELATING TO THE USE OF HERBICIDES

Peter Ackurst
B.C. Forest Service
Vancouver Region
4595 Canada Way
Burnaby, B.C.
V5G 4L9

I think this workshop is a very important contribution to our knowledge of the use of herbicides in the forests of British Columbia. I would like to comment on several issues and concerns that the forest service and the forest community in general has with regards to use of herbicides in our forests.

Research: More research in the field of vegetation management and herbicides and more research into the interaction between our various resources is needed. We do not know all of the answers yet and research projects must continue in search of this knowledge. The Prime Minister and Provincial Premiers acknowledged this fact last week at their first ministers conference when they agreed to greater research and development efforts across Canada. Canada is not keeping up with the rest of the industrialized world in research and development and we in the natural resources sector must strive to keep our research expanding.

New provincial policy initiatives: The initiatives that were announced in September 1987 have had a big impact on the forest service and the forest industry. There are really two new policies, one on stumpage and one on reforestation. I don't want to talk about stumpage at all and I hope no one else talks about stumpage at this workshop. But the second one, on reforestation, makes industry responsible for achieving free-growing status on all regenerated areas both operationally and financially. The forest service also has the same responsibility for large areas under the new policy. The latest quote from the forest service executives is that "the forest service is now the largest licensee of the Province." This means that the forest service manages 16% of the allowable cut of the Province or over 12 million $m^3$ , or approximately 30,000 hectares of area logged per year.

The aim of both industry and the forest service is to put all harvested areas back to a free-growing status as soon as possible. These new policies mean that industry and the forest service will be looking at the most cost effective methods to achieve free-growing plantations. In many cases, this means the use of herbicides, but not in all cases. In many situations, if we do a good job of reforestation we can get a successful plantation without the use of herbicides. We should be striving to do this wherever possible. On some sites there will always be a need for herbicides. And when we deal with the backlog situation we'll have to use herbicides more frequently. I think that it is an important point that we are striving not to use herbicides, but if necessary we will make use of them. The public is very concerned about us using herbicides all of the time.

Public concerns: We have a problem with public concerns over the use of herbicides in the forest. We must be sensitive to the public's concern. The forest service is attempting to deal with these concerns through education programs and further studies. The forest service has a small committee, called the "Forest Issues Steering Committee." It deals specifically with pesticide issues. To date it has been education-oriented, providing pamphlets, slide shows, information centres, demo forests, etc. Our future direction is more towards such things as risk management studies, cost benefit studies, and other kinds of studies.

Before I leave the topic of public concerns, I would like to just comment that we should not over react to the public pressure. In 1987, 488 pesticides permits were applied for, some of which have a three-year duration. Only 22 of these permits were appealed, the board denied 5 permits, amended 2, and there are still 15 permits pending. So 22 out of 488 is not a huge concern.

Staff training: We must keep our staff well-trained on technical facts and figures and with what is happening with current research. In addition, our staff must also be trained in the skills of dealing with the public and the media. Training is a constant concern and it must be kept up and maintained at all times. Certainly, this workshop is a good training session. To carry this point on, I feel there is a need for interpretation of research results to the field practitioners. This workshop is a good example of highly technical research papers that must be translated into field guides and operational principles that field staff can understand and follow. We must go the extra step to technology transfer. The new fisheries/forestry guidelines are just out, and we're all anxiously waiting to see what they are. But these guidelines are a good example of technology transfer. We must be constantly working to transfer new research results to the field.

Finally, cooperation (Bill's theme): We must continue to cooperate on the integrated management of fish and forestry. We can make more progress by cooperatively managing all resources rather than fighting with each other. This year, provincial government money has been allocated to the Ministry of Environment to monitor herbicide use and projects in the field. The forest service feels that it was our money that went from our budget to the Ministry of Environment, but it was all provincial government money given to manage our resources. These monies, if well spent, can contribute to the improvement of integrated management of all resources and I look forward to the results of these surveys and the projects that were carried out in 1987.

To finish up, I would just like to show you what was accomplished province-wide this year (Table 1).

Table 1. Vegetation management activities: 1987 estimates (Ministry and licencees) of hectares treated

| Region | Chemical* | | | | All chemical | Non chemical | Total |
|---|---|---|---|---|---|---|---|
| | Aerial | Hack and squirt | Back-pack | Other | | | |
| Vancouver | 2,000 | 1,200 | 40 | 278 | 3,518 | 1,007 | 4,525 |
| Prince Rupert | 4,713 | 261 | 1,432 | 284 | 6,690 | 985 | 7,675 |
| Prince George | 6,946 | 5,957 | 2,038[a] | 0 | 14,941 | 1,700 | 16,641 |
| Cariboo | 0 | 168 | 76 | 364 | 608 | 1,238[b] | 1,846 |
| Kamloops | 330 | 2,380 | 1,117 | 311 | 4,138 | 1,257[c] | 5,395 |
| Nelson | 265 | 216 | 329 | 10 | 820 | 542 | 1,362 |
| Total | 14,254 | 10,182 | 5,032 | 1,247 | 30,715 | 6,729 | 37,444 |

*Includes some site prep/rehab.

**Includes non-chemical site prep (over 110,000 ha).

[a] All ground except H&S.

[b] Includes 350 ha of grazing.

[c] Includes 100 ha of grazing.

Table 2 is just a different breakdown that shows you the area treated by the Ministry and by licensees.

Table 2. 1987 vegetation management activities: hectares treated by Ministry and licensees

| Region | Ministry | Licensees | Total |
|---|---|---|---|
| Vancouver | 2,184 | 2,341 | 4,525 |
| Prince Rupert | 5,939 | 1,736 | 7,675 |
| Prince George | 5,107 | 11,534 | 16,641 |
| Cariboo | 1,473 | 373 | 1,846 |
| Kamloops | 5,362 | 33 | 5,395 |
| Nelson | 1,147 | 215 | 1,362 |
| Total | 21,212 | 16,232 | 37,444 |

Table 3 gives a cost comparison of the different vegetation management methods. The last one (Table 4) shows that the people who make ROUNDUP are doing quite well in the province of British Columbia. The use of herbicides is 94% ROUNDUP this year. And finally, in summary, I would just like to make the following points:

1. Herbicides are very important to foresters who have the responsibility to establish a new crop of trees on the ground; this is a tool that we must have.

2. This workshop is important to foresters for the purpose of communication and technology transfer.

3. Research into these complex interactions is important so that we can increase our knowledge and thus improve our management.

4. And, finally, cooperation is important between all agencies if we are to progress in the management of our collective resources.

Table 3. Vegetation management activities: 1987 treatment costs ($/ha)* by method

| Method | Range | Average |
|---|---|---|
| Manual | $/ha | $/ha |
| Cutting | 340-1,200 | 620 |
| Girdling | 45- 820 | 375 |
| Herbicide | | |
| Spot gun | 150- 400 | 320 |
| Hack and squirt | 11- 905 | 260 |
| Ground | 250- 760 | 490 |
| Aerial spray | | |
| - fixed wing | 155- 180 | 165 |
| - helicopter | 180- 350 | 255 |

*Included direct on-site costs plus overhead and supervision

Table 4. 1987 vegetation management activities: percent of area treated by chemical (Ministry and licensees)

| Chemical | Percent |
|---|---|
| Vision<br>(glyphosate) | 93.9 |
| Velpar L<br>(hexazinone) | 3.5 |
| Forestamine<br>(2, 4-D amine) | 2.6 |

# INTRODUCTION: FISHERIES ISSUES

Steve Samis
Habitat Management Division
Water Quality Unit
Fisheries and Oceans Canada
555 West Hastings
Vancouver, B.C.
V6B 5G3

I intend to provide a quick overview of the fisheries issues associated with pesticide use in forestry. The three major areas I will touch on are mandates, protection strategies, and problems and solutions.

## 1. Mandate

The federal mandate for fisheries management is the Constitution Act (originally the BNA Act of 1867), which gives the federal government the authority for managing seacoast and inland fisheries, marine science and the administration of the Fisheries Act. Elements of the Fisheries Act predate confederation; today it continues as the principal federal pollution control instrument. Section 31 is concerned with the protection of the physical habitat of fish. The definition of habitat given in the Fisheries Act is all encompassing, including: spawning grounds, nursery areas, rearing areas, food supply and migration areas. Section 33 is the pollution prevention section of the Act and it states that no person shall deposit a deleterious substance in water frequented by fish.

In 1986, the DFO Minister presented the department's Policy for the Management of Fish Habitat. This is a national document with the overall objective of a net gain in the productive capacity of fish habitat. The document points out that habitat damage should be avoided, mitigated or finally compensated for; but that compensation is not an option in the case of chemical pollution and contamination. The Policy states that mitigation must be practised to abate chemical pollution.

DFO inputs to Agriculture Canada in the registration of pesticides federally under the Pest Control Products Act.

The Province manages recreational fisheries, wildlife, and, because of ownership of Crown land and water, also manages waste discharges and pesticide use in British Columbia. Permit appeals under the Environmental Management Act are a provincial responsibility.

## 2. Protection Strategies

How are fisheries protected when pesticides are used? Nationally, as stated, DFO inputs to the registration process. On a regional level under the auspices of the B.C. Pesticide Control Act, a Pesticide Control Committee oversees a federal-provincial referral process for pesticide use on Crown Land. The DFO has input into that process through the Environmental Protection Department of the Environment.

A key fisheries protection strategy in the review of pesticide use near fish habitat is the application of the ten metre pesticide-free zone around waterbodies. This is a management strategy unique to B.C. in Canada. The ten metre pesticide-free zone, can be used to protect both potable waters and fisheries waters. It protects both water quality and riparian areas, or streamside zones.

The riparian zone of streamside vegetation along watercourses, provides five major items for fish: food, cover, shading, bank stability and sediment trapping, all of which are essential to fish production. The riparian zone also provides critical wildlife habitat. Another indirect benefit of the ten metre pesticide-free zone is that it may serve to minimize public appeals of permits through the Environment Management Act's Environmental Appeal Board.

To reiterate, the ten metre pesticide-free zone is a basic requirement around fish habitat and it is a technical as well as administrative management strategy unique to B.C.

A buffer zone, which is a recommendation in B.C., exists outside the ten metre pesticide-free zone, and is measured in addition to the pesticide-free zone. Buffer zones are usually used with the broadcast application of pesticides, as opposed to individual tree treatment methods. Buffer zones serve to protect the integrity of the ten metre pesticide-free zone: their size is determined through agency input and the professional judgment of the applicator. Buffer zones are site specific. The ten metre pesticide-free zone may be waived on a site specific basis where nonbroadcast techniques are used on a small scale.

## 3. Problems and Solutions

Regarding pesticide registration, there is a need for more region-specific toxicology data, to ensure the specific needs of Pacific salmon species are fully addressed. Salmon, because they are seagoing, have different physiological requirements than the commonly tested rainbow trout or fathead minnow. A promising area of testing in toxicology is the rapid sublethal trial. Information is inexpensive to develop but most useful. Also in a strong positive sense is the emerging improved dialogue and working relationship with pesticide manufacturers. Finally, the FRDA toxicity trials that are ongoing funded through CFS and BCFS, dealing with herbicides' sub-lethal effects on Pacific salmon, are very positive developments.

A second problem area relates to agricultural pesticide use. The agriculture industry is the major pesticide user in Canada. However, there are many applicators using toxic insecticides, without necessarily adequate pesticide-free zones on streams. Potential solutions to agriculture pesticide use problems perhaps lie in the training of farmers as certified pesticide applicators, similar to forestry applicators. Perhaps there is also a need for tighter restrictions on agricultural pesticides available. We are monitoring agricultural pesticide runoff and attempting to characterize problem usage.

A third problem area is the constant pressure to relax the ten metre pesticide-free zone. With broadcast pesticide application, the ten metre pesticide free zone around fish habitat is, as I have stated, a requirement, it is not negotiable: whereas the buffer zone is a recommendation, it is flexible and it is based on site specific conditions. The ten metre pesticide-free zone is a technical and administrative strategy. It's a risk management tool. It protects not only water quality but as well, riparian vegetation. Finally, it appears that the ten metre pesticide-free zone is working well to protect fish and wildlife and their habitats. Solutions to the ten metre pesticide-free zone wrangle seem to be: an improved dialogue such as this meeting, to promote better understanding of our management philosophies, and to allow regulators and researchers to discuss their respective views.

In summary, there are federal/provincial mandates to protect fish and wildlife and their habitats. Objectives are achieved through a combination of technical and administrative strategies, supplemented by research, including that directed at minimizing off-target pesticide losses, which may allow smaller buffers outside the ten metre pesticide-free zone.

# AN OVERVIEW OF CARNATION CREEK HERBICIDE STUDY: HISTORICAL PERSPECTIVE, EXPERIMENTAL PROTOCOLS, AND SPRAY OPERATIONS

P.E. Reynolds[1], J.C. Scrivener[2], L.B. Holtby[2] and P.D. Kingsbury[1]

[1]Forest Pest Management Institute
Canadian Forestry Service
1219 Queen Street East
Sault Ste. Marie, Ontario
P6A 5M7

[2] Department of Fisheries and Oceans
Biological Sciences Branch
Pacific Biological Station
Nanaimo, B.C.
V9R 5K6

## ABSTRACT

Research objectives, proposals and protocols for assessing the environmental impacts of applying ROUNDUP (glyphosate) as a control of forest brush species at Carnation Creek were agreed to in 1984 by the British Columbia (B.C.) Ministry of Forests, B.C. Ministry of Environment and Parks, Canadian Forestry Service, Fisheries and Oceans Canada, and the Coumcil of Forest Industries. Carnation Creek is a 10 km$^2$ watershed in the high rainfall cedar-hemlock zone of coastal British Columbia, where the impacts of forestry practices on salmonids have been studied since 1970 under the Carnation Creek Experimental Watershed Project. Project objectives were to improve our understanding of any impacts and the relative magnitude of clearcut logging and post-logging forestry practices on salmon and trout populations and their stream habitat. The Forest Pest Management Institute coordinated and administered the herbicide study as a component to the overall Carnation Creek Experimental Watershed Project. ROUNDUP was applied aerially at 2.0 kg/ha to 41.7 ha of the watershed in September 1984. A 10-m pesticide free zone was maintained along the stream, but two tributary swamps were oversprayed as part of the study design. Short-term direct impacts to stream water, vegetation, soils and stream biota were assessed. Long-term indirect impacts on water quality, erosion processes, and stream biota were studied until at least June 1986.

## INTRODUCTION

In September 1983, the Forest Pest Management Institute (FPMI) of the Canadian Forestry Service (CFS) visited British Columbia (B.C.) to examine forest weed problems in five of the six B.C. forest regions. The visit was sponsored by the B.C. Ministry of Forests (MOF). Following the visit, the MOF proposed that the CFS undertake cooperative research in the province to expedite registration of new forestry herbicides and to assess possible environmental impacts associated with operational use of these herbicides. Use of herbicides was anticipated on productive forest sites within the B.C. coastal zone and a major environmental concern potentially preventing that use of forestry herbicides was possible impacts on salmonids and their habitat. The Carnation Creek Experimental Watershed located on the western side of Vancouver Island was suggested as a prime location for evaluating possible herbicide impacts.

Since 1970, the Carnation Creek Watershed has been an active research site for evaluating the impacts of forest harvesting and other forest practices on salmon and salmon habitat in studies carried out by CFS, by Fisheries and Science branches of Fisheries and Oceans Canada (DFO), and by Water Survey of Canada. Thus, the watershed offered an ideal, extensively studied location, where existing forestry impact studies could be expanded by evaluating the impact of forestry herbicides on fish and fish habitat.

In December 1983, a planning session was held in Victoria, B.C. to discuss research needs with federal and provincial environmental regulators, to solicit their views on study objectives, and to invite their active participation in any future research. Out of this meeting was born the support and the cooperation for the current Carnation Creek Herbicide Study. When the MOF quickly followed through with financial support for the proposed research, other agencies also began contributing resources to the study. Major funding was provided via Monsanto Canada, the manufacturer of ROUNDUP[1] (glyphosate). FPMI was designated as the lead and coordinating agency for carrying out the research and for administering research funds associated with the project.

## WATERSHED DESCRIPTION

Carnation Creek is a small watershed (10 $km^2$), which drains into Barkley Sound on the west coast of Vancouver Island. Annual precipitation is 210-480 cm (Hetherington 1982), 75% of it falls between October and March, and 95% of it falls as rain. Stream flow is highly variable, ranging from .025 $m^3/s$ in summer to 33 $m^3/s$ during winter freshet. Peak flows of 37, 44, and 64 $m^3/s$ with return periods of 5, 12, and 50 years respectively have been observed during the study.

The topography of the basin features rugged terrain of steep slopes to 700 m elevation and a narrow valley bottom through which the stream meanders. The area was heavily glaciated during the Pleistocene period. Slope soils are shallow, coarse textured and highly organic (Oswald 1973). Bedrock is mainly of volcanic origin. Soils in the valley bottom are derived from recent alluvium, which is underlain by gravel deposits (as deep as 4 m), bedrock, and some silty clay deposits.

The pre-harvest vegetation and soils in the drainage were described at the 1982 workshop (Oswald 1982). The primary forest trees in the Carnation Creek drainage basin are western hemlock *Tsuga heterophylla* [Raf.] Sarg.), western redcedar (*Thuja plicata* Donn), amabilis fir (*Abies amabilis* [Dougl.] Forbes), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), Sitka spruce (*Picea sitchensis* [Bong.] Carr.), and red alder (*Alnus rubra* Bong.). The predominant shrubs are salal (*Gaultheria shallon*), stink current (*Ribes bracteosum*), salmonberry (*Rubus spectabilis*), and four species of *Vaccinium.*

Originally, the main channel and tributaries were bordered by red alder, western red cedar and Sitka spruce. This canopy and its thick understory shaded the stream so that light intensities were one sixth of those of adjacent areas with no trees (de Leeuw 1982). By 1984, red alder and salmonberry again shaded the tributaries, but not the main channel.

Anadromous fish use the lower 3.2 km of Carnation Creek and its tributaries. In the mainstem, mean gradient is 0.9% and the bed is characterized by gravel with few particles greater than 100 mm in diameter (Scrivener 1975). Numerous accumulations of fallen trees and buried logs occur in the channel. Extensive gravel bars indicate considerable gravel movement. Valley-wall tributaries, which include Tributaries C, J, and H, and three unnamed tributaries, have gradients ranging from 16.5 to 49% (Fig. 1). These tributaries descend all the way to Carnation Creek or descend for most of their length before crossing a short distance of floodplain. They contain bedrock and boulder bottoms and many fallen trees, some of which store gravel. Often, they also contain cutthroat trout (*Salmo clarki*). The valley-floor tributaries or wall-base channels (Peterson and Reid 1984), which include Tributaries 750, 1600, and 2600, have gradients of <1.5% and are fed by groundwater and ephemeral seepage channels along the valley walls (Hartman et al. 1987). They flow among fallen trees and their beds are organic muck which contain rooted aquatic plants (Brown 1985). Some lower reaches contain sandy gravel bottoms. These valley-floor tributaries are used extensively by salmon and trout.

---

[1] Registered trademark of Monsanto, Inc., St. Louis, MO.

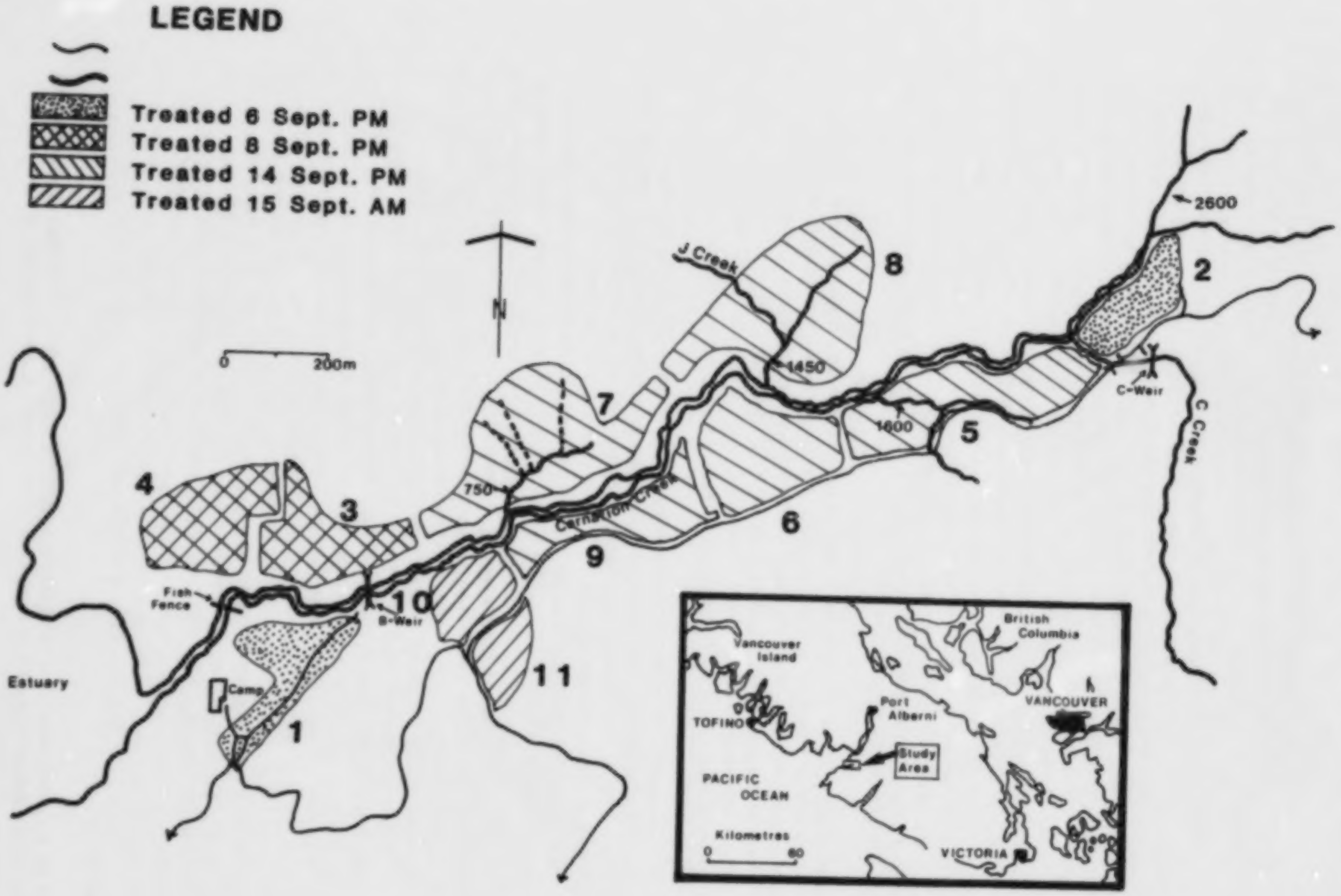

LEGEND
▨ Treated 6 Sept. PM
▨ Treated 8 Sept. PM
▨ Treated 14 Sept. PM
▨ Treated 15 Sept. AM
N
0
200m
J Creek
8
2600
2
1450
1600
5
C-Weir
C Creek
7
750
4
3
Carnation Creek
6
9
Fish Fence
10
B-Weir
Estuary
Camp
1
11
Vancouver Island
British Columbia
TOFINO
Port Alberni
VANCOUVER
Study Area
PACIFIC OCEAN
Kilometres
0
60
VICTORIA

Figure 1. Map of Carnation Creek Watershed showing the locations of glyphosate spray blocks.

# HISTORICAL PERSPECTIVE

## Pre-herbicide Studies

In 1970, forest and fishery managers were growing concerned about the potential impacts of clear-cut logging practices on salmon stocks of western North America. Logging practices were major topics of a salmon and trout symposium in 1968 at the University of B.C. (Northcote 1969) and in 1970 at Corvallis, Oregon (Krygier and Hall 1971), but little detailed information was available from B.C., or from cedar-hemlock watersheds (Narver and Chamberlin 1976). These old-growth forests are typical of coastal North America from the Olympic Peninsula in Washington State to southeast Alaska and the Queen Charlotte Islands (Krajina 1969). During the summer and autumn of 1970, DFO examined fish populations in a number of coastal streams (Narver 1972; Narver and Andersen 1974). Carnation Creek was chosen as the site for a study of the influences of watershed processes on streams and their fish and how these processes are affected by forestry practices. The varied expertise that was required to quantify these processes was obtained through the co-operation of DFO, MOF, CFS, B.C. Ministry of Environment and Parks, Water Survey of Canada, B.C. Universities and MacMillan Bloedel Ltd. Component studies of the pre-herbicide research have been described in detail elsewhere (Scrivener 1988).

Important objectives of the Carnation Creek Project included assisting managers developing resource management strategies for forests and fisheries and communicating results to the scientific/technical community. Technical input during development of the new Coastal Fisheries Forestry Guidelines was continuous (BCMFL et al. 1987). Results have been reported previously during two major workshops (Hartman 1982; Chamberlin et al. 1988), and in 147 articles or reports through a variety of media (Poulin and Scrivener 1988).

As initially planned, the Project had a pre-logging stage (1970-1975), a logging stage (1976-1981) and a post-logging stage (1982-1986). During the logging stage, 41% of drainage area was clearcut in winter as 13 cutblocks using high lead systems (Dryburgh 1982; Hartman et al. 1987). The cutblocks were burned, scarified or left untreated and tree seedlings were planted on the valley bottom and lower slopes. Tributary C and the drainage above E-weir were untreated and served as internal control watersheds (Fig. 1).

The logging plan contained three streamside treatments along the area of stream that was used by salmon and trout. The undisturbed portion (58.4 ha) left the lower 1300 m of Carnation Creek with a variable width strip of deciduous vegetation and some merchantable trees along its banks. This area included the mouth of Tributary 750 (Fig. 1). In the intense streamside treatment (1300-2200 m), streamside alder were girdled and injected with TORDON 22K herbicide[2], and all merchantable timber was harvested. Timber was either felled away from the channel, or if leaning heavily, across it, and then yarded away from the stream to roadside landings. Streambanks and large debris in the channel were damaged. This area (102.7 ha) included Tributaries J and 1600 (Fig. 1). In the careful streamside treatment (2200-3200 m), minor vegetation such as salmonberry was left along the stream and only six merchantable trees that could not be jacked or cabled were felled across the channel and removed. Streamside alders were felled, and during scarification, the logging debris was piled for burning. This area (76 ha) included Tributary 2600. Operationally, treatments two and three are no longer permitted along stream segments that contain salmon.

## Herbicide Study

At the herbicide research meeting in December 1983, the major concern that was expressed by provincial and federal managers of fishery resources involved potential impacts to salmonids or riparian habitat that was oversprayed with herbicide. A policy of maintaining a 10-m pesticide free zone along all fisheries sensitive streams had been established to protect riparian vegetation and water quality. Operational forest managers and spray applicators at the meeting indicated that deliberate overspray of streams visible from the air was not likely, since avoidance of such streams was both feasible and accepted practice. However, possible overspray of tributary back channels that were overgrown by vegetation and used mainly as overwintering habitat for salmonids, was considered unavoidable and probable. The potential impacts of such oversprays, direct or indirect, were unknown and unquantified. Hence, the herbicide research at Carnation Creek was concentrated in these overwintering tributaries. Previous research at Carnation Creek, aimed at assessing logging impacts, had focused more on the main channel.

---

[2] Registered trademark of Dow Chemical Co., Midland, Mich.

The proposed herbicide research both redefined and expanded the 5-year post-logging stage of the Carnation Creek Project. Originally the post-logging stage was to end in 1986, and no post-logging use of herbicides was envisioned. Since post-logging use of forest management practices such as site preparation, scarification, prescribed burning, or herbicides have been routine, expanding the Project provided an opportunity to examine the potential impacts and relative magnitude of these practices.

Following the December 1983 meeting, key researchers met at Carnation Creek in March 1984 to define the research objectives and experimental protocols that were released in April 1984.

## STUDY DESIGN OF HERBICIDE RESEARCH

A decision was made to design a herbicide environmental fate/impact study at Carnation Creek which would:

(1) maintain a 10-m vegetation buffer along the main creek, but
(2) allow for an overspray of certain floodplain tributaries used as overwintering habitat by salmon and trout.

Debate among researchers included whether the herbicide would complicate interpretation of ongoing or future research and what herbicide should be chosen for study, triclopyr (GARLON[3]) or glyphosate (ROUNDUP). After the study began, glyphosate was the herbicide selected because:

(1) the Carnation Creek Steering Committee decided to forego triclopyr testing due to uncertainties in relation to environmental impact and
(2) regional environmental impact data was needed for glyphosate, one of only two herbicides presently federally registered for forestry use.

Concerns about potential herbicide impacts focused on direct or indirect effects. Direct impacts concerned short-term (96 hours) toxicity to fish or stream invertebrates, resulting from overspray or off-target drift, or long-term (up to one year) toxicity resulting from herbicide residue inputs, from winter freshets into side channels used by overwintering salmonids or emerging fry. In general, regulators wanted information on short-term impacts, while researchers designing the study were more concerned with long-term impacts. Researchers were concerned that the long-term fate of herbicide residues in a coastal watershed had never previously been quantified, and did not know if toxic levels would enter the tributaries during and following winter freshets. Other regulators were concerned about sublethal effects, a longer-term impact of the herbicide, on fish movements, reproduction, etc. However, researchers concluded that long-term fate of herbicide residues had to be properly quantified before any sublethal effects could be assessed.

---

[3] Registered trademark of Dow Chemical Co., Midland, Mich.

Indirect impacts were accorded greater importance by researchers designing the experiment. These impacts on salmonids were likely to be far more significant than direct effects because herbicides are used to reduce brush species that maintain stability of the stream channel and quality of salmonid habitat (Gregory et al. 1987; Hartman et al. 1987). Indirect impacts concerned long-term habitat (i.e., riparian or stream) changes resulting from overspraying overwintering tributaries.

**Objectives:**

With this background, the objectives of the Carnation Creek ROUNDUP Study were defined to include:

(1) monitoring off-target glyphosate deposit;
(2) monitoring short-term glyphosate residues in oversprayed tributaries and those entering Carnation Creek from these tributaries;
(3) monitoring short-term, immediate effects of aerial ROUNDUP application on salmon fry behavior, movements and mortality in relation to measured glyphosate residue levels in flowing tributaries and isolated pools in the experimental area;
(4) monitoring short-term aquatic invertebrate drift resulting from ROUNDUP exposure;
(5) monitoring the movement of glyphosate residues into side channels following major fall and winter storm events;
(6) measuring the persistence and dissipation of glyphosate in riparian foliage and soils;
(7) assessing habitat changes induced by glyphosate (water temperature, changes in riparian vegetation, erosion, sediment inputs, stream chemistry, algal populations, aquatic and terrestrial invertebrate fish-food, litter inputs, etc.) in stream and side channels; and
(8) monitoring fish utilization of side channels for 2 years following glyphosate application relative to habitat changes or relative to glyphosate residues in water and stream sediment.

## EXPERIMENTAL PROTOCOLS

Specific protocols called for the following:
(1) Maintenance of a 10-metre vegetation buffer on either side of Carnation Creek;
(2) Overspray of two side channels designated as 750 and 1600;
(3) A third side channel, designated as 2600, to serve as a control side channel for 1600 and 750 (2600 is located above the portion of the watershed to be aerially treated with herbicide);
(4) Mortality and/or movements of fish to be recorded for 1600, 750 and 2600 during and immediately after spraying (96 hours);
(5) Invertebrate drift to be quantified for 1600 and 2600 during and immediately after spraying (96 hours);
(6) Streamwater samples to be collected from Carnation Creek, 1600, 750 and 2600 during and immediately after spraying (96 hours) for residue analysis;
(7) Off-target deposit samples to be collected from within the 10-metre vegetation buffer and from within the main channel of Carnation Creek following the herbicide application for residue analysis;
(8) Soil samples to be collected periodically for one year after herbicide treatment for residue analysis;
(9) Erosional changes affecting Carnation Creek to be measured periodically prior to and after herbicide treatment;

(10) Streamwater and stream sediment samples to be collected from 1600, 750 and 2600 after major storm events (freshets) for the first six months after herbicide treatment for residue analysis;

(11) Streamwater and stream sediment samples to be collected twice monthly from 1600, 750 and 2600 for seven through twelve months after herbicide treatment for residue analysis;

(12) Streamwater samples to be collected periodically from Carnation Creek, 1600 and 2600 prior to and for 2 years after herbicide treatment for analysis of dissolved ions;

(13) Stream temperature to be monitored continuously in 1600 and 2600 tributaries until October 1986;

(14) Periphyton samples to be collected periodically from Carnation Creek, 1600 and 2600 prior to and after herbicide treatment for analysis;

(15) Alder and salmonberry leaves to be collected periodically prior to and after herbicide treatment for residue analysis;

(16) Detrital inputs to be measured periodically for 1600, 750 and 2600 prior to and after herbicide treatment;

(17) Aquatic invertebrate samples to be collected periodically from Carnation Creek, 1600, 750 and 2600 prior to and after herbicide treatment for identification and quantification;

(18) Input to the stream of terrestrial insects to be measured periodically for 1600, 750 and 2600 prior to and after herbicide treatment;

(19) Long-term fish mortality and utilization of 1600, 750 and 2600 to be monitored periodically after herbicide treatment, and compared with pre-treatment utilization patterns; fish mortality and utilization to be studied in reference to long-term residues and habitat changes; and

(20) Herbicide efficacy, crop tolerance and crop growth to be evaluated periodically after herbicide treatment.

## SPRAY OPERATIONS

Carnation Creek watershed was aerially treated with ROUNDUP in early September 1984 using an Alpine Helicopter Bell-47 helicopter equipped with a MICROFOIL BOOM[4] to minimize aerial herbicide drift into fish-bearing waters. Spraying was carried out by Rotor Vegetation Control of Calgary under the direction of the FPMI. A map showing actual spray blocks is presented in Figure 1 and hectares, spray dates, spray times, air temperature, wind conditions, etc. are presented in Tables 1-3.

### Protocol Deviations and Their Rationale

Research was carried out as described in the April 1984 protocols with only minor deviations. The watershed was treated at 2.0 kg a.i./ha of ROUNDUP versus 1.7 kg a.i./ha to more closely approximate the maximum recommended label rate and to enhance herbicide efficacy (spraying was late season and some of the vegetation was already senescent). However, it should be noted that previous MacMillan-Bloedel data supplied to FPMI indicates that an application rate of 1.7 kg a.i./ha is optimal for coastal weed control.

Tributaries C and 1450, side channels of Carnation Creek, were not oversprayed as originally planned. These areas were known or found to contain salmonids. The study thereby

---

[4] Registered Trademark of Union Carbide, Inc., Ambler, Pa.

Table 1. Treatment conditions (all meteorological data was obtained from recording instruments at Station A; Scrivener 1988)

| | |
|---|---|
| Herbicide (a.i.) | glyphosate (356 g/L) |
| Treatment rate | 2.0 kg a.i./ha |
| Spray volume | 258.25 L/ha |
| Aircraft | Bell-47 helicopter |
| Boom and nozzles | MICROFOIL BOOM, 7.9 m in length, .060 hayrake nozzles |
| Orientation of nozzles | 180° |
| Boom pressure | 172.5 kPa |
| Airspeed | 40.2 km/h |
| Swath width and altitude | 12.1 m; 6-18 m |
| Weather (prior) | Sunny and calm winds immediately prior to Sept. 6; intermittent showers on Sept. 7 and each day from Sept. 9 through Sept. 12; sunny with NE winds to 22 km/h on Sept. 13 |
| (at times of spraying) | Sept. 6 - time: 1900-2005 h; air temperature: 15°C; wind conditions: 7 km/h E to W; skies: cloudy, overcast, intermittent sun; precipitation: none |
| | Sept. 8 - times: 1416-1445 h and 1913-1940 h; wind conditions: 7-10 km/h E to W; skies: overcast, black clouds, threatening showers; precipitation: none |
| | Sept. 14 - time: 1430-1931 h; air temperature: 21°C; wind conditions: 5-11 km/h E to W; skies: sunny, overcast, white clouds; precipitation: none |
| | Sept. 15 - time: 1041-1101 h; air temperature: 14°C; wind conditions: < 5 km/h E to W; skies: sunny; precipitation: beginning at 1345 h |
| (after) | Winds increasing in speed and changing direction (W to E) by 1130 h on Sept. 15; cloudy and overcast, with rain clouds moving in from sea by 1200 h; rain showers began at 1345 h on Sept. 15, and heavy rain continued through 1500 h on Sept. 16 |

Table 2. Spray Data for Carnation Creek Watershed

| Spray block | Spray date (Sept.) | Time period | Application rate (kg. a.i./ha) (Glyphosate) | Tank mix | Spray volume (I.G.) | Block size[a] (ha) | Air temp. (°C) | Wind conditions km/h |
|---|---|---|---|---|---|---|---|---|
| 1 | 6 | 1900-1925 | 2.0 | 1 | 140 | 2.5 | 15 | ≤ 7 |
| 2 | 6 | 1935-2005 | 2.0 | 1 | 175 | 3.1 | 15 | 7 |
| 3 | 8 | 1416-1445 | 2.0 | 1 | 300 | 5.3 |  | 10 |
| 4 | 8 | 1913-1940 | 2.0 | 1 | 185 | 3.2 |  | 7 |
| 5 | 14 | 1430-1539 | 2.118[b] | 2 | 505 | 8.9 | 21 | 10 |
| 6 | 14 | 1646-1715 | 2.118 | 2 | 235 | 4.1 | 21 | < 7 |
| 7 | 14 | 1730-1814 | 2.118/2.125[c] | 2/3[c] | 290 | 5.1 | 21 | 11 |
| 8 | 14 | 1840-1849 | 2.125 | 3 | 63 | 1.1 | 21 | 10 |
| 9 | 14 | 1900-1931 | 2.125 | 3 | 285 | 5.0 | 21 | 7 |
| 10 | 15 | 1041-1050 | 2.125 | 3 | 100 | 1.7 | 14 | < 5 |
| 11 | 15 | 1053-1101 | 2.125 | 3 | 100 | 1.7 | 14 | < 5 |

[a] Based upon spray volume and calibration of spray system (56.8 I.G./ha).

[b] Residual spray solution in the tank and pumping system was assumed to be 50 Imperial gallons (I.G.) after each tank mix was used. Therefore, the concentration of active ingredient (a.i.) remaining subsequently changed the rate for tank mix #2 and tank mix #3.

[c] In spray block #7, the area closest to Carnation Creek received 100 I.G. from the 2nd tank mix while the area farthest from Carnation Creek received 190 I.G. from the 3rd tank mix for a total of 290 I.G.

Table 3. Spray data for specific Carnation Creek sprayblocks

| | Spray Block 5 | | Spray Block 6 | | Spray Block 7 | |
|---|---|---|---|---|---|---|
| | Tributary 1600 | | Connection with 1600 | | Tributary 750 | |
| Spray period | Time | Duration (Min) | Time | Duration (Min) | Time | Duration (Min) |
| 1 | 1433-1438 | 5 | 1646-1652 | 6 | 1730-1735 | 5 |
| 2 | 1443-1445 | 2 | 1654-1659 | 5 | 1737-1741 | 4 |
| 3 | 1451-1453 | 2 | 1703-1707 | 4 | 1757-1806 | 9 |
| 4 | 1459-1503 | 4 | 1709-1715 | 6 | 1810-1814 | 4 |
| 5 | 1507-1510 | 3 | - | - | - | - |
| 6 | 1514-1518 | 4 | - | - | - | - |
| 7 | 1522-1526 | 4 | - | - | - | - |
| 8 | 1530-1534 | 4 | - | - | - | - |

Note: Spraying began closest to Carnation Creek and moved upslope away from Carnation Creek.

conformed more closely to the regulatory policy of DFO. Because of reduced spraying near 1450, tank mix solution was left over at the conclusion of spraying. This mixed solution was sprayed onto an adjoining portion of the watershed (spray block 11) and one original spray block (spray block 9) was enlarged (spray block 10) to accommodate the left over solution. Rinseate from the helicopter spray tanks and boom was sprayed onto portions of the adjoining spray block (Number 11).

## LITERATURE CITED

B.C. Ministry of Forests and Lands (BCMFL). B.C. Ministry of Environment and Parks. Federal Department of Fisheries and Oceans. Council of Forest Industries. 1987. British Columbia Coastal Fisheries and Forestry Guidelines. 101 p. Available from BCMFL. Victoria. British Columbia.

Brown, T.G. 1985. The role of abandoned stream channels as over-wintering habitat for juvenile salmonids. M.S. thesis, University of British Columbia, Vancouver, British Columbia. 134 p.

Chamberlin, T.W. (Ed.). 1988. Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biological Station, Nanaimo, British Columbia. 239 p.

deLeeuw, A.D. 1982. The effects of logging on benthic invertebrate stream drift and trout growth rates in two small west coast Vancouver Island streams, p. 240-256. In: G.F. Hartman (Ed.). Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404 p.

Dryburgh, J.G. 1982. Carnation Creek logging and silvicultural treatment program, p. 36-44. In: G.F. Hartman (Ed.). Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404 p.

Gregory, S.V., G.A. Lambert, D.C. Erman, K.V. Koski, M.L. Murphy and J.R. Sedell. 1987. Influence of forest processes on aquatic production, p. 233-256. In: E.O. Salo and T.W. Cundy (Eds.). Streamside Management-forestry and fisheries interactions. Contribution No. 57, Institute of Forest Resources, AR-10, University of Washington, Seattle, Washington 98195. 471 p.

Hartman, G.F. (Ed.). 1982. Proceedings of the Carnation Creek Workshop: a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404 p.

Hartman, G.F., J.C. Scrivener, L.B. Holtby and L. Powell. 1987. Some effects of different streamside treatments on physical conditions and fish population processes in Carnation Creek, a coastal rain-forest stream in British Columbia, p. 330-372. In: E.O. Salo and T.W. Cundy (Eds.). Streamside Management - forestry and fishery interactions. Contribution No. 57, Institute of Forest Resources, AR-10, University of Washington, Seattle, WA 98195. 471 p.

Hetherington, E.D. 1982. A first look at logging effects on the hydrologic regime of Carnation creek experimental watershed, p. 45-63. In: G.F. Hartman (Ed.). Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404 p.

Krajina, V.J. 1969. Ecology of forest trees in British Columbia, p. 1-146. In: V.J. Krajina and R. Brooke (Eds.). Ecology of Western North America. Vol. 2, No. 1 and 2. Department of Botany, University of British Columbia, Vancouver, British Columbia. 349 p.

Krygier, J.T. and J.D. Hall (Eds.). 1971. Proceedings of a symposium Forest Land Uses and Stream Environment, Oct. 19-21, 1970. Oregon State University, Corvallis, Oregon. 252 p.

Narver, D.W. 1972. A survey of some possible effects of logging on two eastern Vancouver Island streams. Fish. Res. Board Can. Tech. Rep. 323:55 p.

Narver, D.W. and B.C. Andersen. 1974. Fish populations of Carnation Creek and other Barkley Sound streams - 1970-1973: Data record and progress report. Fish. Res. Board. Can. MS Rep. 1303:115 p.

Narver, D.W. and T.W. Chamberlin. 1976. Carnation Creek--An experiment towards integrated resource management. Can. Fish. Mar. Ser. Circular No. 104. Pacific Biological Station, Nanaimo, British Columbia. 20 p.

Northcote, T.G. (Ed.). 1969. Symposium on salmon and trout in streams. Feb. 22-24, 1968. H.R. MacMillan lectures in fisheries. University of British Columbia, Vancouver, British Columbia. 388 p.

Oswald, E.T. 1973. Vegetation and soils of Carnation Creek watershed. Pac. For. Res. Cent., Can. For. Ser., Victoria, British Columbia, Int. Rep. 43:38 p.

Oswald, E.T. 1982. Preharvest vegetation and soils of Carnation Creek watershed, p. 17-35. In: G.F. Hartman (Ed.). Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, B.C. 404 p.

Peterson, N.P. and L.H. Reid. 1984. Wall-base channels: Their evolution, distribution and use by juvenile coho salmon in the Clearwater River, Jefferson County, Washington, p. 227-242. In: J.M. Walton and D.B. Houston (Eds.). Proceedings of the Olympic Wild Fish Conference. Fisheries Technology Program, Peninsula College, Port Angeles, WA 98362. 308 p.

Poulin, V.A. and J.C. Scrivener. 1988. An annotated bibliography of the Carnation Creek fish-forestry project - 1970 to 1988. Can. Tech. Rep. Fish. Aquat. Sci. 1640:35 p.

Scrivener, J.C. 1975. Water, water chemistry and hydrochemical balance of dissolved ions in Carnation Creek watershed, Vancouver Island, July 1971-May 1974. Can. Fish. Mar. Ser. Tech. Rep. 564: 141 p.

Scrivener, J.C. 1988. The Carnation Creek experimental watershed project: a description and history from 1970 to 1986, p. 1-10. In: T.W. Chamberlin (Ed.). Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biological Station, Nanaimo, British Columbia. 239 p.

# CARNATION CREEK FLOODPLAIN HYDROLOGY

## SEPTEMBER 1984 - SEPTEMBER 1985

Eugene D. Hetherington
Pacific Forestry Centre
Canadian Forestry Service
506 West Burnside Rd.
Victoria, B.C.
V8Z 1M5

## ABSTRACT

The precipitation, streamflow, and groundwater regimes in the lower Carnation Creek floodplain are described for the 1-year period encompassing the application and monitoring of the environmental behaviour of the herbicide glyphosate. Rainfall just prior to the first herbicide application on the floodplain moistened the soil on well-drained areas and initiated ponding and flow of water in side channel depressions and swamps. The next rainfall on blocks containing monitored tributaries and seasonally flooded soil residue sampling sites came within 24 hours after herbicide application. Rainfall during the next 10 weeks was above average, providing ample opportunity for off-site movement and leaching of any mobile herbicide residues. However, precipitation then remained below average for the rest of the study period. Surface water was continuously present in floodplain depressions and side channels until the following summer, with groundwater levels rising and falling in response to rainfall events. Surface soil layers on well-drained soil sampling sites would have remained moist but unsaturated and above the groundwater table throughout most of the study period. Of the three seasonally flooded soil sampling sites, two remained saturated and were frequently flooded until the following summer, while the other experienced unsaturated periods, particularly during the first 3 weeks after application, and only occasional flooding. The implications of these soil water regimes are that any mobile herbicide residues would have leached vertically downward on well-drained sites and under non-saturated soil conditions, but would have tended to move laterally from seasonally flooded stations during flooding and saturated conditions.

## INTRODUCTION

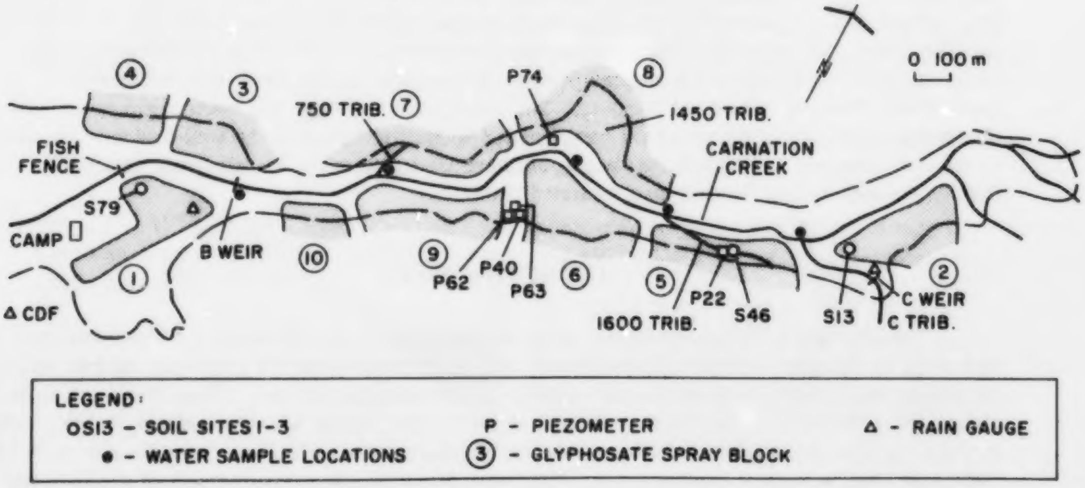
The information presented herein provides an a posteri description of the floodplain hydrology to aid other workers in interpreting the environmental fate of glyphosate and its major metabolite aminomethylphosphonic acid (AMPA). Precipitation and streamflow data were collected during the 1984-1985 herbicide study period as part of the regular Carnation Creek Project monitoring program. In addition, some groundwater measurements were taken from June to early October 1984 and 1985 as part of another study. However, direct on-site measurements of groundwater levels during the residue sampling period are lacking. The nature of the floodplain microtopography makes it difficult to generalize about off-channel flooding on the basis of information available, but some reasonable speculations can be made about specific sites. Probable groundwater and flooding conditions within soil sampling stations at sampling times have been estimated by piecing together the hydrological data that are available for the period of interest, anecdotal comments from field notes (H. Klassen, V.A. Poulin & Assoc., Vancouver B.C., personal communicahave been particularly helpful. Additional surface water observations and groundwater measurements were also collected in 1987 at soil residue sampling sites to provide further clues.

The objectives of this paper are to present precipitation and streamflow data for September 1984 to September 1985, describe the nature of groundwater behaviour in the Carnation Creek floodplain and evaluate probable hydrologic conditions at soil residue sampling sites for the specific days of sample collection.

## STUDY AREA

### Floodplain

The lower floodplain of Carnation Creek (Fig. 1) is about 3000 m long, 50 ha in area, and has an average channel slope of 1.9% (Brown 1985). In the past, the stream has moved back and forth across the floodplain, leaving numerous old channels separated by slightly raised sand and gravel beds. Vegetation has occupied the raised areas while many of the old channel depressions have become swamps or ephemeral stream channels which occupy about 1.3 ha at low winter flow periods (Brown 1985). These coarse alluvial deposits are as deep as 4 m (Scrivener and Brownlee 1980). In the depressions, accumulations of fine organic material have resulted in muck blankets as much as 1 m deep with a variety of ground vegetation described in detail by Brown (1985). The soils on the raised areas occupied by trees are alluvial regosols from about 0 to 60 cm deep with sandy loam textures (Oswald 1973). These coarse soils have high infiltration and percolation rates and allow rainwater to move quickly down to the groundwater table. The main channel



0 100 m
④
③
750 TRIB. ⑦
P74
⑧
1450 TRIB.
FISH FENCE
CARNATION CREEK
S79
CAMP
B WEIR
⑩
⑨
P62
P40
P63
⑥
⑤
P22
S46
S13
②
C WEIR
C TRIB.
1600 TRIB.
①
△ CDF
LEGEND:
OS13 – SOIL SITES 1–3
P – PIEZOMETER
△ – RAIN GAUGE
● – WATER SAMPLE LOCATIONS
③ – GLYPHOSATE SPRAY BLOCK

Figure 1. Map of Carnation Creek floodplain showing locations of piezometers, rain gauges, soil and water sampling sites and approximate spray block boundaries (modified from Brown 1985).

morphology and debris accumulations determine where and at what flow levels the stream will overflow its banks and enter some of these old channels or simply cover the floodplain. The degree of overflow varies both along the length of the channel and over time as channel geometry changes due to shifting of gravel and debris during storm flows. During major rain storms, surface runoff in side channels will also increase, expanding the area of surface water flow and extending it beyond defined channel depressions.

The 750-m, 1450-m, and 1600-m side tributaries vary in size and flow, each having contributing side slope drainage areas that exceed those in the floodplain itself. The 1450-m tributary has a total drainage area of about 50 ha which includes the gauged 24-ha J Creek watershed. However, flow dispersal across and into an elevated alluvial fan results in only a portion of the flow occurring in the ephemeral channel from which water samples were collected for herbicide residue analysis. Drainage areas for the 750-m and 1600-m tributaries are approximately 9 and 13 ha and their channel lengths in the floodplain are about 100 m and 250 m, respectively. The 750-m channel carries water fairly directly from the side slope to the main Carnation Creek channel, while the 1600-m channel meanders across the floodplain and contains considerable amounts of woody debris. Water from Carnation Creek enters the 750-m channel when flows exceed 7 $m^3\ s^{-1}$ and the upper 1600-m channel when flows exceed 20 $m^3\ s^{-1}$ (Brown 1985). Carnation Creek water also enters the 1450-m channel in its lowest portion and the lower part of 1600-m channel at flows less than 20 $m^3\ s^{-1}$, but the flows at which this occurs have not been evaluated.

The soil herbicide residue sampling stations #1 to #3 and #7 to #9 (S13 and S79 in Fig. 1) are located on raised well-drained sandy-gravel beds. More information on soil characteristics at these stations is given by Feng and Thompson (1989). Stations #4 and #5 (S46 in Fig. 1) are situated in a gently sloping ill-defined and seasonally flooded side channel, and station #6 (S46 in Fig. 1) is located downstream immediately adjacent to a more well-defined portion of the same channel.

### Climate and Streamflow

The climate features mild summers and mild wet winters with frequent frontal rain storms. Annual precipitation on the floodplain occurs mostly as rain and has ranged from about 2100 to 3850 mm. Average precipitation for the total watershed is about 20% higher than on the low-elevation floodplain (Hetherington 1988). Maximum annual daily rainfall on the floodplain has ranged from 80 to 220 mm. Some snow occurs at higher elevations in the watershed almost every year but the snowpack is usually short-lived and probably represents less than about 5% of the total precipitation. Snow has occurred on the floodplain in 8 of 14 winters prior to 1985. Annual water yields (total streamflow) have ranged from 2100 to 4000 mm (depth over the drainage area) and measured flows from less than 0.03 to 65 $m^3 s^{-1}$. Both streamflow and groundwater levels respond rapidly to storm rainfall, rising and falling in concert with variations in rainfall intensity or cessation (Hetherington 1982). The frequency of major stormflow events (flows exceeding 6.7 $m^3 s^{-1}$ at weir B) has ranged from 7 to 21 per year with an average number of 14 (Hetherington 1988).

## METHODS

A comparison of precipitation data from gauges at the main weather station (CDF), weir B, and weir C on the floodplain (Fig. 1) indicated that the daily station CDF data adequately represent floodplain precipitation. Hence, CDF data are used in this paper because they were readily accessible and had been verified. Hourly precipitation values recorded at the field camp were adjusted using ratios of CDF/camp daily totals. Streamflow data from weir B were used to represent floodplain flow conditions.

Floodplain groundwater behaviour was assessed in several ways. Data from an on-going study of summer groundwater recession in the floodplain (Hetherington 1982, 1987) were used to study groundwater responses during rain storms and relationships to stormflow during part of the herbicide study period. In particular, recordings of water levels at stations #63 and #74 plus manual measurements at stations #62 and #63 were used (Fig. 1). Groundwater measurements were taken during the winter of 1983-84 at a different set of piezometers located throughout the floodplain (Brown 1985). One of these piezometer locations (#22) was chosen as the site for soil sample station #4, but water levels were not measured, while a second (#40) was situated only 13 m from my piezometer #62. Piezometers #62 and #40 are located in a drainage depression analogous to that at soil stations #4 and #6, piezometer #63 is in a depression near #62, and piezometer #74 is in a depression on a raised alluvial fan from the J Creek (1450-m) tributary.

Observations of groundwater levels and conditions collected subsequent to the 1984-85 study period were used to evaluate probable conditions during that time. Water levels were measured at piezometer #40 in 1986 and 1987. Additional measurements of groundwater levels and observations of surface water conditions were made from June to November 1987 at the soil residue sampling sites to supplement the 1983-84 data. Soil pits about 180 cm deep were dug in June 1987 near soil stations #1 to #3 and #7 to #9 to monitor groundwater levels at these locations. Photographs of the soil stations taken in 1984 indicated that field conditions in 1987 at the sites had changed very little since 1984. Brief field notes on soil station surface water conditions at times of herbicide residue soil sample collections were also used in this assessment (H. Klassen, personal communication).

The above information on groundwater and streamflow was used to select weir B stream discharge values which coincide with three water-related conditions at soil stations #4 and #6: (1) station completely flooded (flow 1.7 m$^3$ s$^{-1}$ at #4 and #6); (2) soil not flooded but saturated to the surface (flow >0.085 m$^3$ s$^{-1}$ at #4 and >1.13 m$^3$ s$^{-1}$ at #6); (3) water content below saturation in the top 15 cm of soil (flow <0.051 m$^3$ s$^{-1}$ at #4 and <0.17 m$^3$ s$^{-1}$ at #6). Water begins to flow across one corner of station #4 when weir B flows exceed 0.085 m$^3$ s$^{-1}$, whereas surface water enters station #6 only when flows exceed 1.13 m$^3$ s$^{-1}$. Even for the non-saturated condition, the soils would have been wet to the touch (confirmed by H. Klassen, personal communication), but subsurface water movement or leaching would be slower than for saturated conditions. The derived groundwater conditions are only estimates. Actual measurements of water table and soil hydrologic properties would be needed to be more definitive.

All times indicated on the graphs and referred to in the text are Pacific Standard Time (PST).

## RESULTS AND DISCUSSION

### General Nature of Floodplain Groundwater Level Behaviour

During dry periods or several days after major rainfall, the groundwater table in the floodplain exhibits a general uniform rate of decline. Groundwater will naturally be closer to the surface in depressions than under raised areas. Contributing causes of groundwater rises are rainfall directly onto the floodplain, subsurface seepage from side slopes and water from the main channel at higher flows. Side slope seepage will be more rapid in winter under wet conditions and much slower during drier summer months. The groundwater table rises rapidly during storm events.

much slower during drier summer months. The groundwater table rises rapidly during storm events. Increases in groundwater level can range from only a few centimetres if water levels are already high or rainfall light to over 100 cm if levels are low and rainfall heavy (Fig. 2). In addition, infrequent light rains during the summer dry period may cause a slight change in groundwater levels with little accompanying change in streamflow (Fig. 2).

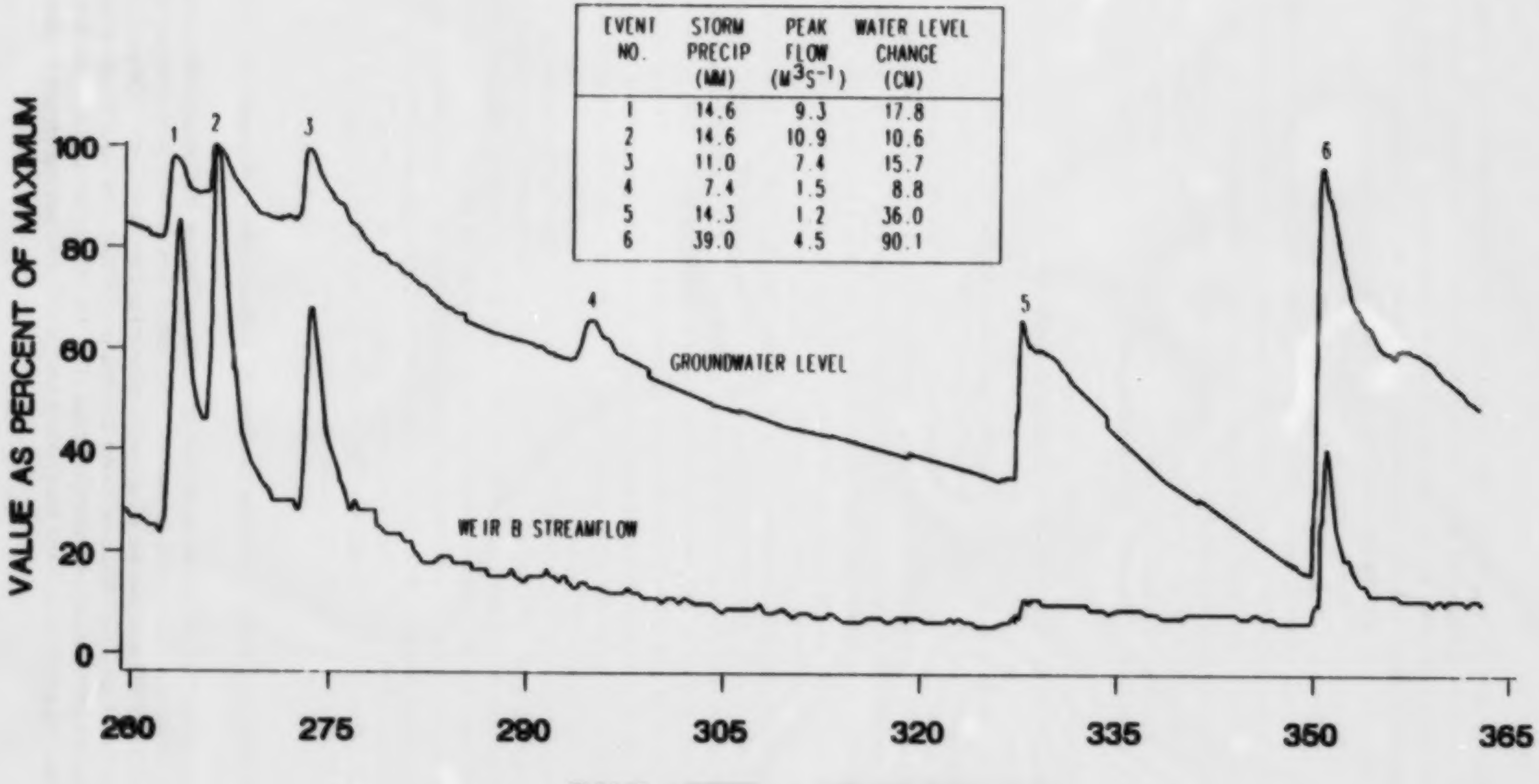
The rate of groundwater rise in side channel depressions decreases sharply once surface flow in these channels begins (Fig. 3). Changes in groundwater levels are fairly closely correlated with streamflow and the onset of side channel flow occurs when streamflows are still very low (Fig. 3). Relative changes in groundwater levels can also vary markedly over short distances as shown by a comparison between sites #62 and #40 only 13 m apart (Fig. 4). In this case, surface flow begins sooner at the upstream #40 site causing a drop in relative rates of water level rise until flow also occurs at site #62. These data highlight the difficulty of generalizing about floodplain groundwater levels during storms and the need for site-specific measurements.

## Hydrologic Conditions Prior to Herbicide Application

Below-average precipitation during July and August 1984 resulted in the following conditions by September 4: very low streamflow (0.024 $m^3$ $s^{-1}$ ), water table about 20 cm below the surface in side drainage channel depressions at soil station #4 (piezometer #22) and piezometer #62, and over 100 cm below at piezometer #74. The 39 cm of rain on September 4-5 increased streamflow (Fig. 5), brought the water table to the surface in drainage channels and depressions as indicated at piezometers #62 and #63 (Fig. 6), saturated the soil at sampling station #4 and moistened the soil at the other soil sampling stations prior to herbicide application on blocks 1-2 (Reynolds et al. 1989) on September 6. Surface ponding in drainage depressions was sustained through September 15. The 22 mm of rain on September 7-8, ending at 0600 PST September 8, resulted in a modest peak streamflow (Fig 5), caused surface flow in drainage depressions, brought the water table temporarily to the surface at piezometer #74, and wetted vegetation just 11 hours prior to herbicide application on blocks 3 and 4 (Reynolds et al. 1989) on September 8. Light showers on September 9 and 10 kept the system moist. A further 17 mm of rain early on September 12 caused a small increase in streamflow (Fig. 5) and sustained ponding in drainage depressions, although groundwater levels at piezometer #74 dropped well below the surface by September 14 (Fig. 6). On September 14, the day of herbicide application on blocks 5-9 (Reynolds et al. 1989) and over 2 days since the last rain, streamflow had decreased (Fig. 5) but the soil was saturated at sampling stations #4 and #6, wet at other sampling stations and water was still ponded in depressions (Fig. 6), including most of the 750-m and 1600-m tributary channels. J Creek was flowing and some but not all of its ephemeral channels across the alluvial fan had surface flow. Streamflows at the time of herbicide application on September 14 were estimated at 0.001 $m^3$ $s^{-1}$ for the 750-m tributary, 0.01 $m^3$ $s^{-1}$ for the 1450-m tributary and 0.016 $m^3$ $s^{-1}$ for the 1600-m tributary (Feng et al. 1986), and measured as 0.15 $m^3$ $s^{-1}$ at weir B, 0.02 $m^3$ $s^{-1}$ at weir J and 0.016 $m^3$ $s^{-1}$ at weir C. The next rain on September 15 began after 1330 PST or within 3 or 4 hours after herbicide application on blocks 10 and 11.

## Hydrologic Conditions During the Year After Herbicide Application

Weather during the year after herbicide application (September 1984 to September 1985) exhibited some interesting anomalies. The annual precipitation from October 1984 to September 1985 of 2307 mm was the third lowest recorded at Carnation Creek. Of particular importance for the herbicide study, however, is the fact that precipitation was actually above average during the first 10 weeks after herbicide application (Fig. 7). The maximum daily rainfall of 120 mm occurred on October 7 and the October total of 542 mm was the second highest on record for this



| EVENT NO. | STORM PRECIP (MM) | PEAK FLOW ($M^3S^{-1}$) | WATER LEVEL CHANGE (CM) |
|---|---|---|---|
| 1 | 14.6 | 9.3 | 17.8 |
| 2 | 14.6 | 10.9 | 10.6 |
| 3 | 11.0 | 7.4 | 15.7 |
| 4 | 7.4 | 1.5 | 8.8 |
| 5 | 14.3 | 1.2 | 36.0 |
| 6 | 39.0 | 4.5 | 90.1 |

Figure 2. Relative comparison of site #63 groundwater and weir B streamflow fluctuations June to September 1985.

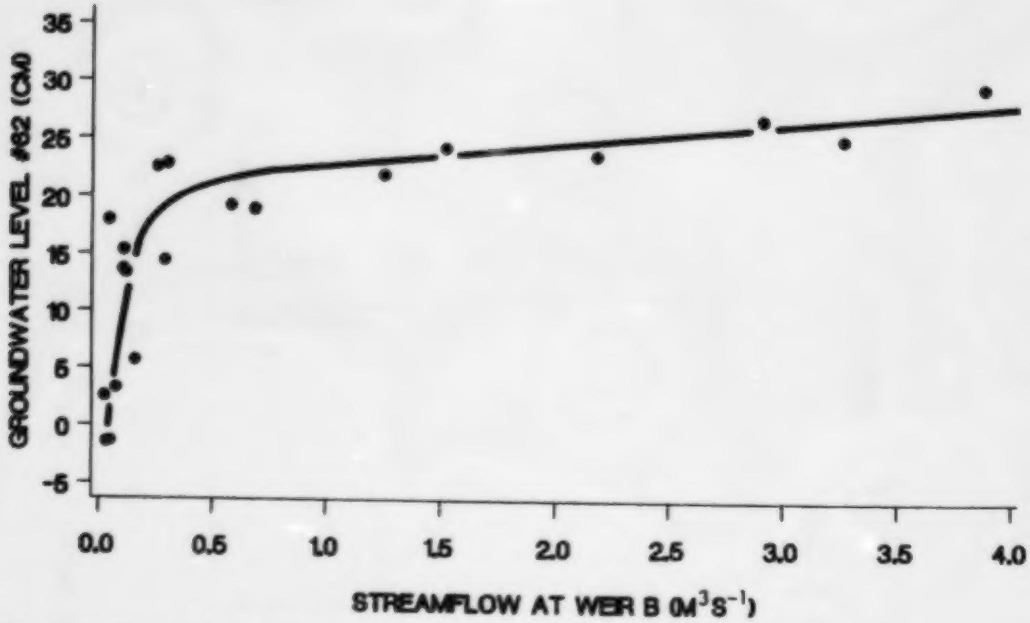


Figure 3. Relationship between storm peak groundwater levels at site #62 and peak flows at weir B.

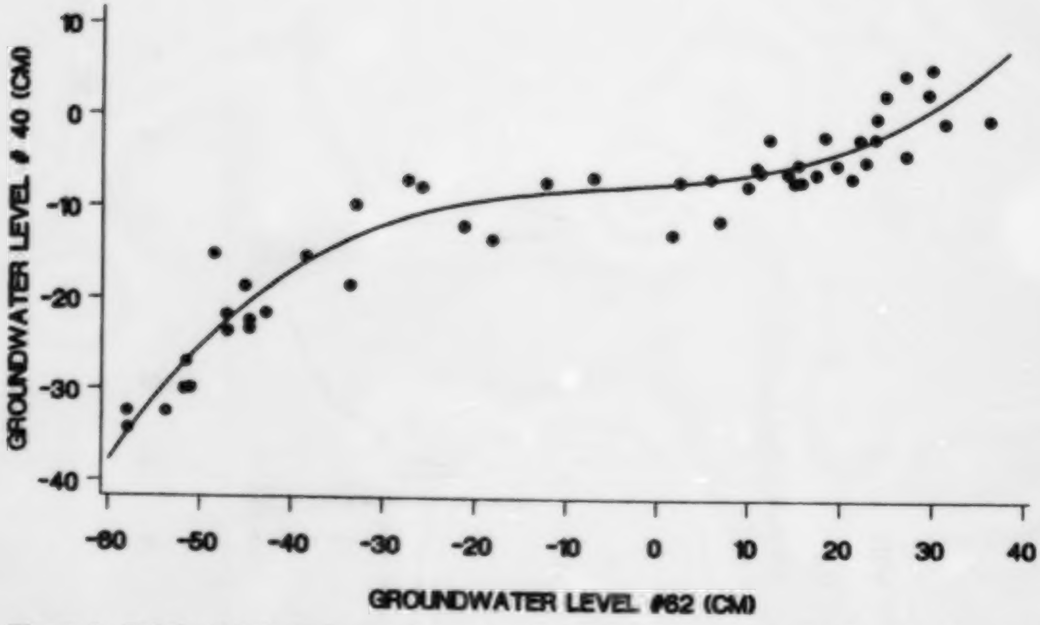


Figure 4. Relationship between groundwater levels at sites #62 and #40 in the Carnation Creek floodplain.

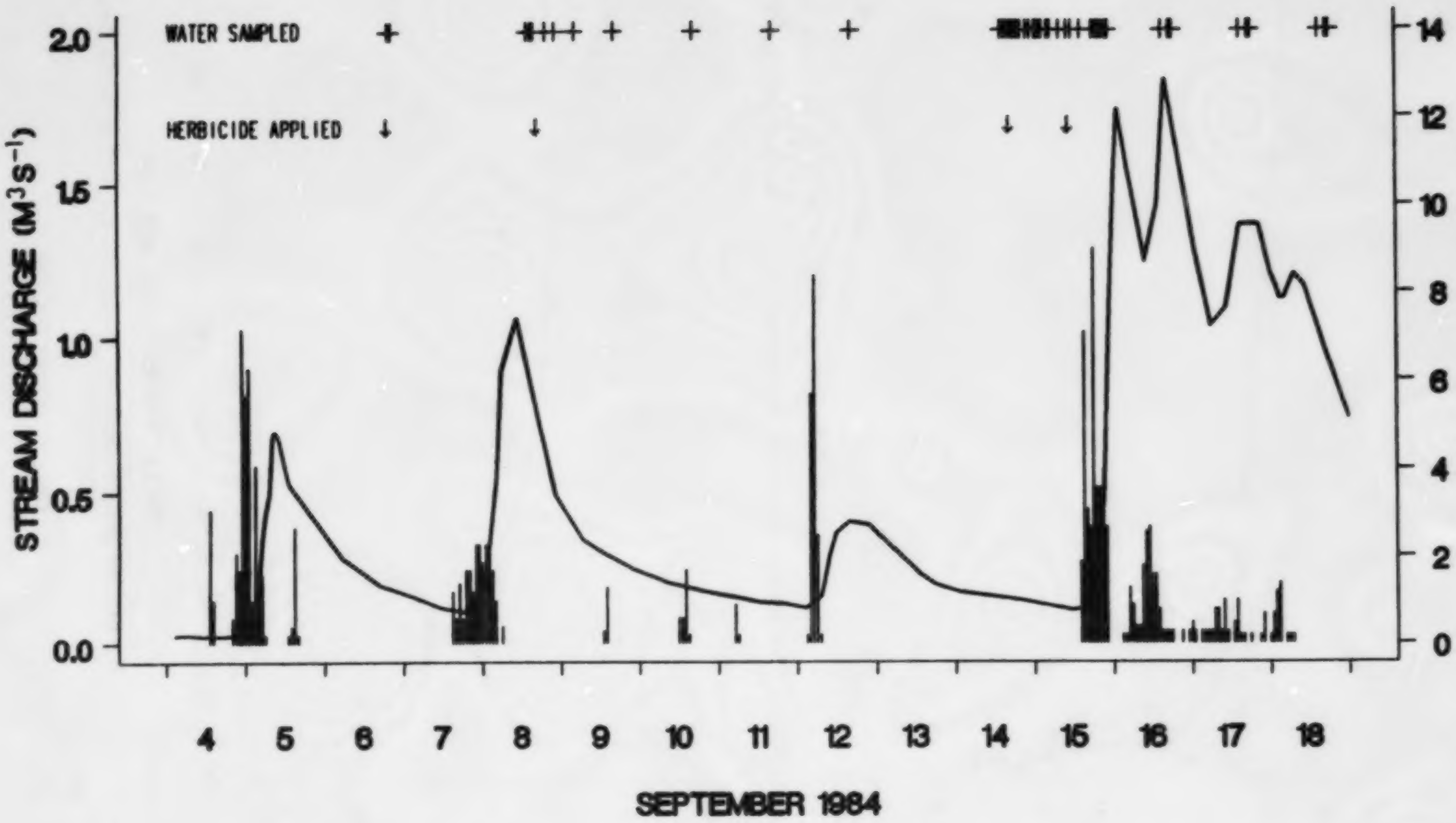


Figure 5. Streamflow, precipitation and water sampling times from September 4-18, 1984.

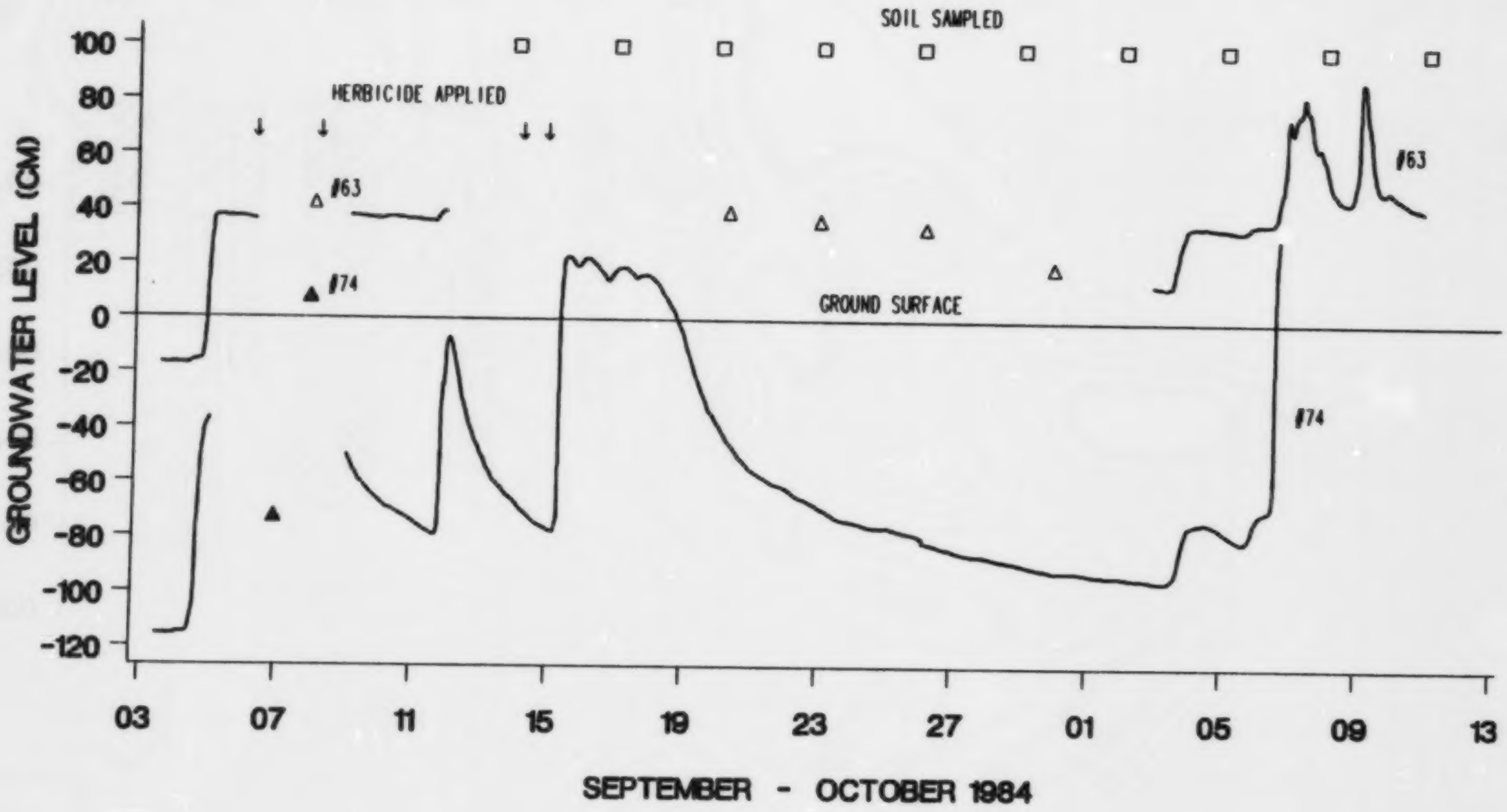


Figure 6. Groundwater levels at site #63 and site #74 and times of soil sampling at sites #4 and #6 from September 3 to October 11, 1984.

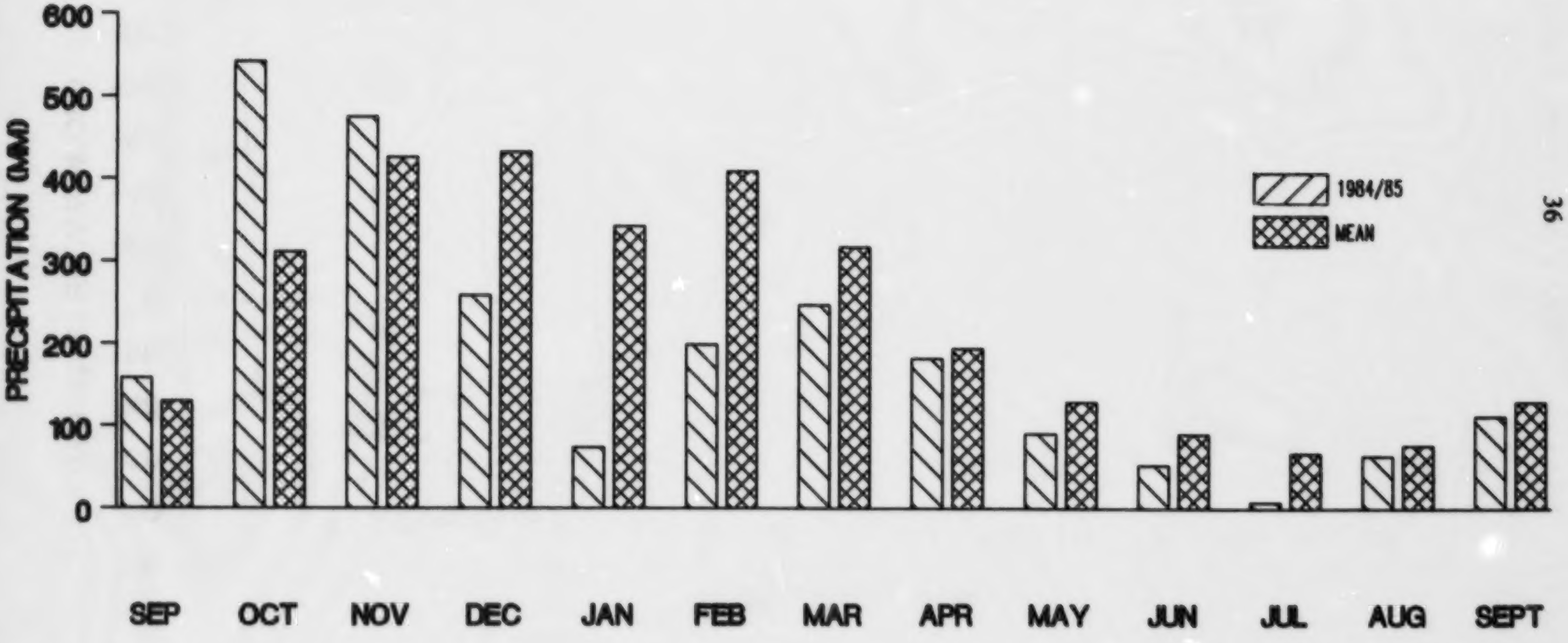


Figure 7. Monthly precipitation on the floodplain for the period September 1984 to September 1985 in relation to long-term mean values.

month. Thus, there was ample opportunity for lateral movement and leaching of herbicide residue during this rainy period. Precipitation then remained below average through September 1985, with January and February 1985 values being the lowest on record (Fig. 7). The winter of 1984-85 was one of the two snowiest on record in terms of frequency of snowfalls and duration of the snowpack at higher elevations. Snow occurred on the floodplain on three occasions (Dec. 28-30, Jan. 5 and Feb. 8-9) but remained on the ground for only a short time. At higher elevations (stations D and L), snow occurred as early as October 24, 1984 and a snowpack persisted most of the winter and into April 1985, with maximum depths up to 40-50 cm.

For reference, daily precipitation and the streamflow hydrograph for the year after herbicide application are presented in Figures 8 and 9, respectively. During this year, there were seven rain storms of sufficient magnitude to produce streamflows exceeding 6.7 $m^3$ $s^{-1}$ (Fig. 9), the third lowest number on record and well below the average of 14 which meet this criterion. Storms for which water samples were collected for herbicide residue analysis (Feng et al. 1989) include six of these major events (Fig. 9). The highest peak flow of 28.1 $m^3$ $s^{-1}$ has a return period of about once every 2 years and is below the average annual peak of 35 $m^3$ $s^{-1}$ (Hetherington 1988).

## Hydrologic Conditions Relating to Water Sampling Times

Sampling of stream water for herbicide residue analysis included a short-term intensive monitoring period from September 6-18, collection related to seven stormflow events (flows exceeding 3 $m^3$ $s^{-1}$) and bi-weekly collections from March to September 1985 (Feng et al. 1989). The times of water sample collection are indicated in Figures 5, 8 and 9 in relation to streamflow and precipitation. Precipitation and streamflow data for the seven sampled storms are summarized in Table 1. Flow values in the various streams at the time of herbicide application have been given above.

Table 1. Summary of data for storms during which water samples were collected for herbicide residue analysis (flows exceeding 3 $m^3$ $s^{-1}$ at weir B) from September 1984 to September 1985

| Storm event no. | Date | Days after 14.09.84[a] | Peak flow ($m^3s^{-1}$) | Rainfall (mm) | | |
|---|---|---|---|---|---|---|
| | | | | 24 h total[b] preceeding | Storm total | Cumulative[c] from 14.09.84 |
| 1 | 7.10.84 | 23 | 22.9 | 54 | 193 | 293 |
| 2 | 9.10.84 | 25 | 28.1 | 50 | 95 | 426 |
| 3 | 2.11.84 | 49 | 4.5 | 39 | 51 | 695 |
| 4 | 12.11.84 | 59 | 8.1 | 46 | 46 | 859 |
| 5 | 19.11.84 | 66 | 7.7 | 51 | 47 | 963 |
| 6 | 7.12.84 | 84 | 9.5 | 59 | 78 | 1168 |
| 7 | 11.02.85 | 150 | 9.1 | 56 | 49 | 1532 |

[a] Date of second herbicide application.
[b] For the 24 h preceeding the time that threshold flow was attained.
[c] Up to 0800 PST on the day threshold was attained.

The first rainfall after herbicide application on blocks 5 to 9, which contain the side tributaries of interest, began at 1335 PST September 15 and ended 8 hours later at about 2145 PST with a total of 38 mm (Fig. 5). Thus, the rain started 21, 24 and 25 hours after spraying occurred on blocks 5, 7 and 8 containing the 750-m, 1600-m and 1450-m tributaries, respectively (Reynolds et al. 1989). Streamflows at weirs B, C and J increased modestly in response to this rainfall (Fig. 5). Further rain September 16, 17 and 18 sustained these raised flow levels during the remainder of the first 96-hour intensive sampling period ending in the evening of September 18 (Fig. 5). Water was also ponded and flowing in most side channel drainage depressions in the floodplain during this rainy period.

Water flow and ponding was sustained in the 750-m, 1600-m, and C Creek and most other drainage depressions in the floodplain through the winter until near the end of May 1985. Flow fluctuations in the side channels would have generally followed the pattern of flow in the main channel (Figs. 9, 10). Subsequent low precipitation during the summer (Fig. 8) resulted in many side channel depressions drying up in June 1985 and surface water was absent from most of the floodplain during August 1985 (Fig. 10). Pools enabled water samples to be collected from the 1600-m tributary during the summer, but surface channels of the 750-m and C Creek tributaries were dry at 4 and 5 of the last 8 sampling times, respectively. Water moves more quickly through the relatively short 750-m and 1450-m floodplain channels to the main stream than through the longer, more tortuous 1600-m channel.

### Hydrologic Conditions Relating to Soil Sampling Times

Conditions at soil sampling stations #4 and #6 are described separately from those at stations #1 to #3 and #7 to #9 because of differing site characteristics and sampling times. The times of soil sample collection for residue analysis (Feng and Thompson 1989) for stations #4 and #6 are indicated in Figures 6, 8, 9 and 10 in relation to streamflow, precipitation and groundwater levels and listed specifically in Table 2. The times for the other stations are listed in Table 3. In Table 2, the data on the percentage of time streamflows exceed specified values were derived from flow duration curves.

On soil station #4, located partly in the drainage channel, surface water was flowing across the lower portion of the site at the time of herbicide application on September 14. This flow decreased during the next 24 hours but it is possible that some surface flow was sustained during this period. Surface flow across the station increased with the rain on the evening of September 15, with complete flooding of the station for at least 4 hours on September 16 and sustained surface flow until September 22. The water table remained within 10 cm of the surface at the highest part of the station from September 14 through September 22, sustaining water saturation to the soil surface. Under these conditions, water would have tended to move laterally over the station surface or through the top few centimetres of soil rather than downward into the soil. The top 15 cm of soil in station #4 would have subsequently remained saturated until the next summer (Table 2). A part of this station was subject to surface flow for a considerable portion of this time, which meant that soil samples were taken from one area of the station while the rest of the area was under water. These results suggest that water and any herbicide residue in solution or suspension in the water would have continued to move laterally rather than downward in the top soil layer.

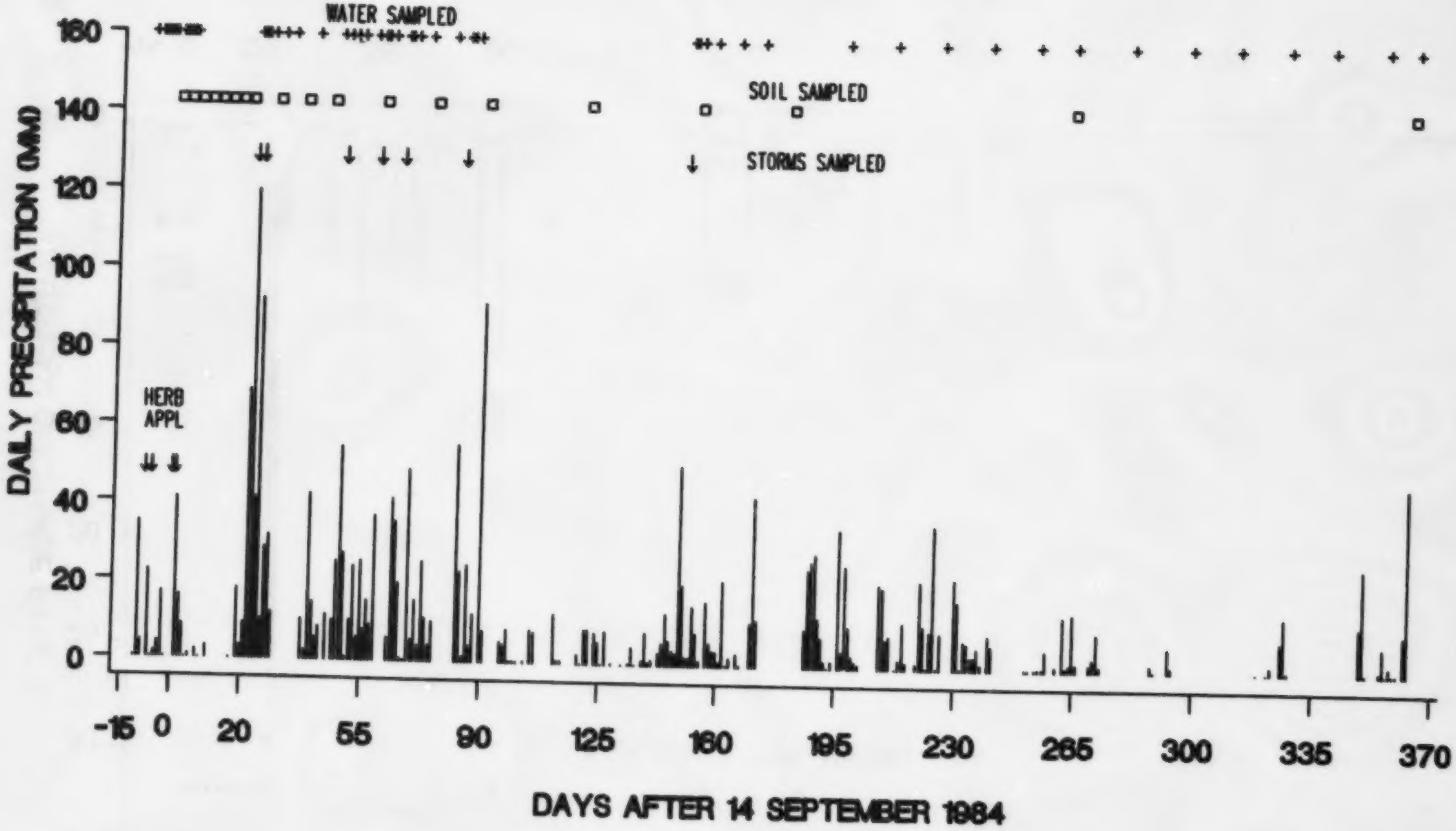


Figure 8. Daily precipitation on the Carnation Creek floodplain from September 1984 to September 1985 plus indicated times of sampled storm events, water sampling and soil sampling at sites #4 and #6.

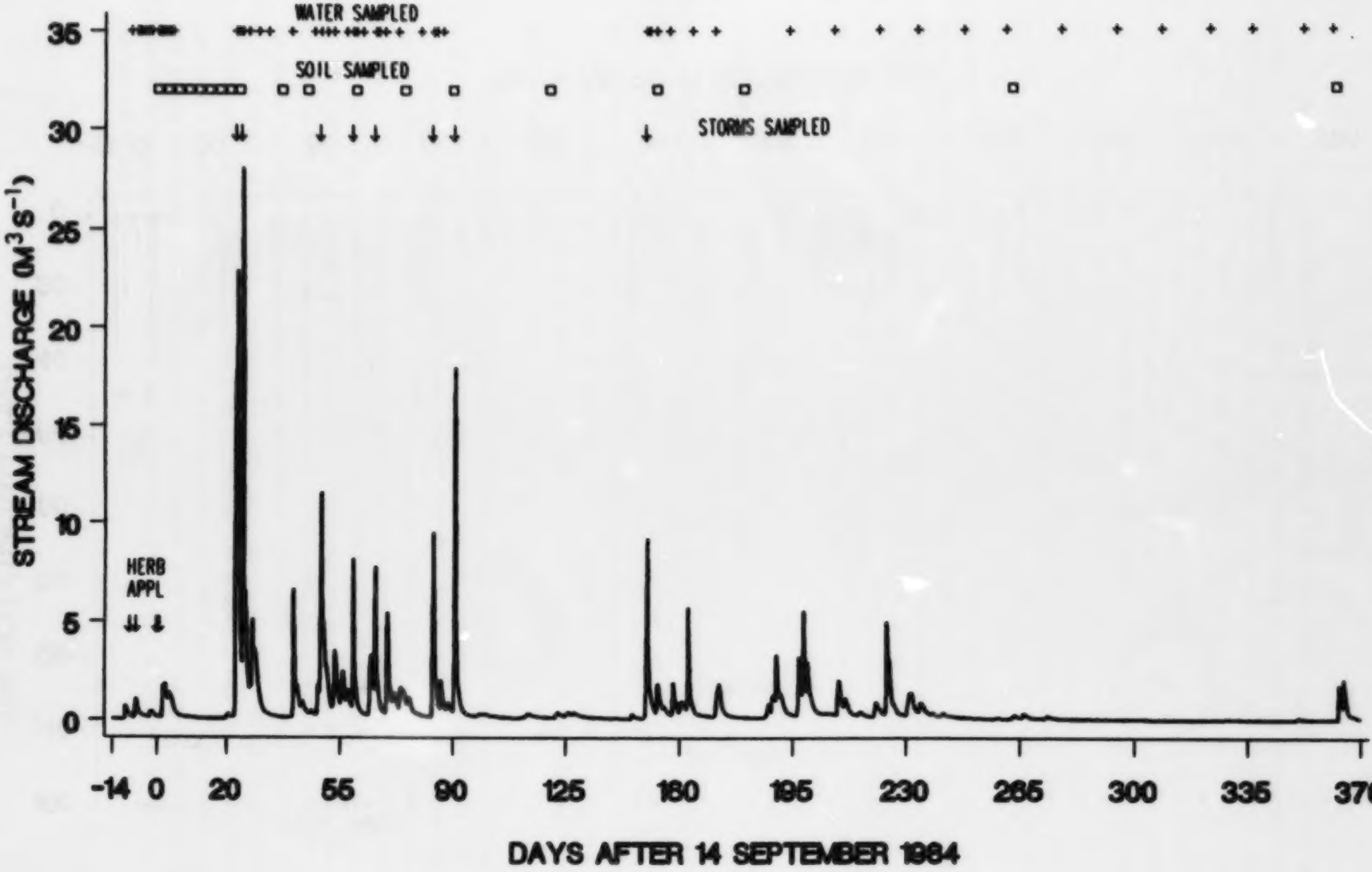


Figure 9. Streamflow at Carnation Creek weir B for September 1984 to September 1985 plus indicated times of sampled storm events, water sampling and soil sampling at sites #4 and #6.

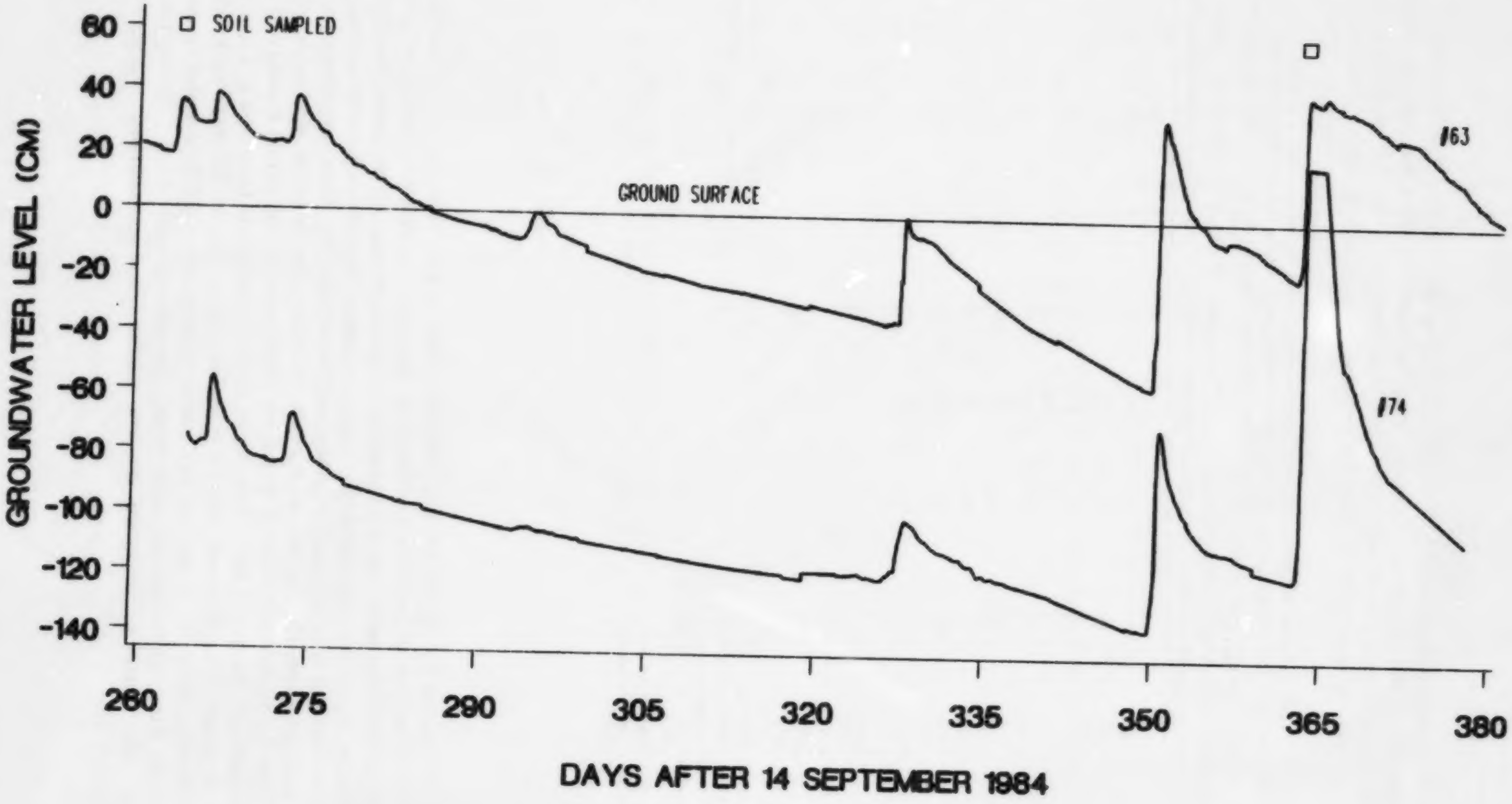


Figure 10. Groundwater levels at sites #63 and #74 from June to September 1985 plus indicated times of soil sampling at sites #4 and #6.

Table 2. Hydrologic conditions related to times of soil sample collection at stations #4 and #6.

| Date | Days after 14.09.84[a] | Cumul. precip.[b] (mm) | Weir B flow[c] ($m^3 s^{-1}$) | Soil water conditions plot #4<br>Flooded[d] | Sat.[e] | Non-sat.[f]<br>(% time since Sept. 14) | Sample time cond.[g] | Soil water conditions plot #6<br>Flooded | Sat. | Non-sat.<br>(% time since Sept. 14) | Sample time cond. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14.09.84 | 0 | 0 | 0.15 | 0 | 100 | 0 | S | 0 | 0 | 100 | N |
| 17.09.84 | 3 | 66 | 1.17 | 18 | 100 | 0 | S | 18 | 44 | 41 | S |
| 20.09.84 | 6 | 67 | 0.26 | 9 | 100 | 0 | S | 9 | 41 | 20 | S |
| 23.09.84 | 9 | 70 | 0.12 | 6 | 100 | 0 | S | 6 | 27 | 34 | N |
| 26.09.84 | 12 | 73 | 0.08 | 5 | 98 | 0 | S | 5 | 20 | 50 | N |
| 29.09.84 | 15 | 73 | 0.07 | 4 | 78 | 0 | S | 4 | 16 | 60 | N |
| 02.10.84 | 18 | 73 | 0.06 | 3 | 65 | 0 | S | 3 | 14 | 67 | N |
| 05.10.84 | 21 | 104 | 0.25 | 3 | 62 | 0 | S | 3 | 12 | 67 | S |
| 13.10.84 | 29 | 509 | 3.31 | 24 | 72 | 0 | F | 24 | 30 | 49 | F |
| 21.10.84 | 37 | 509 | 0.15 | 21 | 78 | 0 | S | 21 | 28 | 40 | N |
| 29.10.84 | 45 | 605 | 0.38 | 20 | 82 | 0 | S | 20 | 28 | 40 | S |
| 13.11.84 | 60 | 859 | 1.45 | 25 | 87 | 0 | S | 25 | 36 | 30 | S |
| 28.11.84 | 75 | 1080 | 1.32 | 25 | 89 | 0 | S | 25 | 38 | 24 | S |
| 13.12.84 | 90 | 1304 | 0.44 | 23 | 91 | 0 | S | 23 | 35 | 21 | S |
| 12.01.85 | 120 | 1367 | 0.12 | 19 | 93 | 0 | S | 19 | 28 | 26 | N |
| 14.02.85 | 153 | 1552 | 0.56 | 16 | 93 | 0 | S | 16 | 23 | 32 | S |
| 13.03.85 | 180 | 1689 | 0.15 | 14 | 94 | 0 | S | 14 | 22 | 28 | N |
| 04.06.85 | 263 | 2159 | 0.19 | 12 | 94 | 0 | S | 12 | 19 | 28 | S |
| 13.09.85 | 363 | 2337 | 0.04 | 9 | 73 | 20 | N | 9 | 14 | 47 | N |

[a] Date of second herbicide application [b] Cumulative precipitation [c] Flow values for 1200 PST [d] Plot completely flooded [e] Saturated to the surface with water table at or near the surface (assumed saturated when flooded) [f] Top 15 cm of soil not completely saturated [g] Condition of top 15 cm of soil: F = Flooded, S = Saturated, N = Completely saturated

Note: Percentages for the three soil water condition categories do not total 100% because the saturated category includes the time the site was flooded and the intermediate stage between saturated and non-saturated is not included.

On soil station #6, the top 15 cm of the higher half of the station was in a non-saturated condition from the time of herbicide application on September 14 until near midnight September 15. The rising groundwater table and 1600-m tributary flow from the rain on September 15 then saturated the soil to the surface and completely flooded the station for at least 4 hours on September 16. The surface soil layer remained saturated until September 21. Thus, water would have tended to move downward into the soil during the first 24 hours after herbicide application and then laterally over the surface and through the top few centimetres of soil during flooded and saturated conditions over the next 5 days. The station would subsequently have been in a non-saturated condition for much of the time until the first major rain storm October 20, three weeks after herbicide application (Table 2). Water and any residue it contained would have tended to move vertically downward through the top soil layer during this non-saturated period. During the rest of the winter, site conditions fluctuated between saturated and non-saturated with occasional flooding (Table 2).

Groundwater data for piezometer #63 (Figs. 6, 10) and data presented by Brown (1985) support the idea that surface water was likely continually present in most side channel depressions during the fall and winter period. Under these conditions, even those sections of these channels temporarily without surface water would have remained saturated in the centre of the channel or depression.

At soil stations #1 to #3 and #7 to #9, it is highly unlikely that the top 15-30 cm of soil were flooded and they seldom reached the point of saturation. Rain water would have moved vertically downward through the soil profile to the groundwater table below, carrying with it any mobile herbicide residue. Cumulative rainfall at sampling times for these stations is summarized in Table 3.

Table 3. Cumulative precipitation at time of soil sample collection at stations #1 to #3 and #7 to #9

| Date | Days after 06.09.84[a] | Cumul. precip.[b] (nm) | Date | Days after 06.09.84 | Cumul. precip. (nm) |
|---|---|---|---|---|---|
| 06.09.84 | 0 | 0 | 13.10.84 | 37 | 554 |
| 09.09.84 | 3 | 24 | 21.10.84 | 45 | 554 |
| 12.09.84 | 6 | 46 | 05.11.84 | 60 | 779 |
| 15.09.84 | 9 | 87 | 20.11.84 | 7 | 1009 |
| 18.09.84 | 12 | 112 | 12.12.84 | 97 | 1258 |
| 21.09.84 | 15 | 115 | 04.01.85 | 120 | 1408 |
| 24.09.84 | 18 | 118 | 03.02.85 | 150 | 1471 |
| 27.09.84 | 21 | 118 | 05.03.85 | 180 | 1734 |
| 30.09.84 | 24 | 118 | 04.06.85 | 271 | 2205 |
| 02.10.84 | 26 | 119 | 13.09.85 | 371 | 2383 |
| 05.10.84 | 29 | 149 | | | |

[a] Date of first herbicide application.
[b] Cumulative precipitation.

## ACKNOWLEDGMENTS

I wish to express my appreciation to R. Leahy, J. Lough and R. Rowswell for the many hours of taking measurements and observations of floodplain groundwater behaviour, often under adverse weather and field conditions, and to Tom Brown for his assistance.

# REFERENCES

Brown, T.G. 1985. The role of abandoned stream channels as over-wintering habitat for juvenile salmonids. M.Sc. thesis, Univ. of British Columbia, Fac. For., Vancouver, B.C. 134 p.

Feng, J.C. and D.G. Thompson. 1989. Persistence and dissipation of glyphosate in foliage and soils of a Canadian coastal forest watershed. This proceedings.

Feng, J.C., D.G. Thompson and P.E. Reynolds. 1989. Fate of glyphosate in a Canadian forest stream ecosystem. This proceedings.

Hartman, G.F. and T.G. Brown. 1987. Use of small, temporary, floodplain tributaries by juvenile salmonids in a west coast rain-forest drainage basin, Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. 44: 262-270.

Hetherington, E.D. 1982. A first look at logging effects on the hydrologic regime of Carnation Creek Experimental watershed. pp. 45-63 in G. Hartman (ed.) Proceedings of the Carnation Creek Workshop, a 10 year review, February 24-26, 1982. Pacific Biological Station, Nanaimo, B.C.

Hetherington, E.D. 1988. Hydrology and logging in the Carnation Creek watershed - what have we learned? pp. 11-15 in T.W. Chamberlin (ed.) Proceedings of the workshop: Applying 15 years of Carnation Creek results.

Oswald, E.T. 1973. Vegetation and soils of the Carnation Creek watershed (a progress report). Can. For. Serv., Pac. For. Res. Cent., Internal Report BC-43, Victoria, B.C. 38 p.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. Overview of Carnation Creek herbicide project: historical perspective, experimental protocols and spray operations. This proceedings.

Scrivener, J.C. and M.J. Brownlee. 1980. A preliminary analysis of Carnation Creek gravel quality data, 1973-1980. pp. 195-226 in Proceedings from the conference: Salmon-spawning gravel: a renewable resource in the Pacific Northwest?, Oct. 6-7, 1980. Seattle, Washington.

# FATE OF GLYPHOSATE IN A FOREST STREAM ECOSYSTEM

J.C. Feng[1], D.G. Thompson[2] and P.E. Reynolds[2]

[1]Northern Forestry Centre
Canadian Forestry Service
5320-122nd Street
Edmonton, Alberta T6H 3S5

[2]Forest Pest Management Institute
Canadian Forestry Service
1219 Queen Street East
Sault Ste. Marie, Ontario P6A 5M7

## ABSTRACT

Residues of glyphosate and its major metabolite aminomethyl phosphonic acid (AMPA) were monitored in stream water, bottom sediments and suspended sediments for a one year period following aerial application of glyphosate (2.0 kg/ha) to the Carnation Creek watershed of Vancouver Island, British Columbia. Analysis of deposit collector samples indicated an actual deposit of 1.88 kg/ha within the target zone and that less than 0.1% of the full rate impinged on surfaces beyond 8 m from the spray zone boundary. The highest concentrations of glyphosate (6.80 μg/g dry mass) were observed in bottom sediments of a directly sprayed tributary, with low residue levels (<0.2 μg/g) persisting in this substrate throughout the monitoring period. Suspended sediment samples collected from the main stream channel, indicated low levels of glyphosate input (0.10 μg/L) in conjunction with the first five storm events (23-66 days post application). The highest stream water residue observed (162 μg/L) occurred in a directly sprayed tributary, 2 h post-application and decreased rapidly to 37 μg/L after 16 h. Transient increases in glyphosate concentrations were associated with first rainfall event (39 mm) which occurred 23 h post-application. Subsequent dissipation of residues in the two tributaries receiving direct glyphosate applications was rapid, such that no quantifiable residues were found after 96 h post-application. No quantifiable residues were found in tributaries buffered with a 10-m vegetation strip during the monitoring period.

## INTRODUCTION

Glyphosate (ROUNDUP[1]) is a forestry herbicide recently registered in Canada for site preparation and conifer release (Malik and Vanden Born 1986). Federal and provincial regulatory agencies require further research on the aquatic fate and persistence relevant to the operational use of glyphosate under local geographical and climatic conditions. Although the behavior of glyphosate in aquatic systems has been investigated in the United States and elsewhere (Comes et al. 1976; Rueppel et al. 1977; Edwards et al. 1980; Ghassemi et al. 1981; Norris et al. 1983; Newton et al. 1984), this aspect has not been studied in Canada. Research on the aquatic fate and impact of glyphosate is of particular importance in coastal temperate rainforest ecosystems of British Columbia. In such areas a number of factors, including steep-sloped terrain, high rainfall (>2000 mm), and proximity of treatment areas to salmon spawning streams, combine to approximate a worst case scenario with respect to aquatic ecosystem impacts following silvicultural chemical applications. The aquatic persistence and transport patterns of glyphosate under these situations are unknown. Also, the relative degree of stream contamination resulting from input sources such as direct over-spray of stream channels, off-target deposit, lateral movement and mass transfer from surrounding treated areas have not been quantified under these conditions.

---

[1] Registered trademark of Monsanto Co. Inc., St. Louis, Missouri

A vegetation buffer strip along streams may be used to reduce contamination via off-target drift and runoff. Current regulatory guidelines in British Columbia require the establishment of a 10-m pesticide-free zone with appropriate buffers, usually 100-m, to achieve this goal. These guidelines may unduly restrict silvicultural treatment of the highly productive forest lands that border the intensive network of streams in coastal regions.

Establishment of an effective buffer must balance environmental concerns with the need for maximum utilization of lowland forests. The goal of effective buffering has become feasible with the development of dispersal systems, such as the MICROFOIL BOOM[2], which are designed to reduce chemical drift and the width of buffer strips required to protect streams and lakes (Payne et al. 1986).

## OBJECTIVES

The specific objectives of this study were:

1. To assess the on- and off-target deposit of glyphosate following an operational application for conifer release in a typical, coastal British Columbia watershed.

2. To determine the residue levels and subsequent dissipation of glyphosate and its major metabolite AMPA during the initial 96 hour period in four dissimilar streams following aerial application with a MICROFOIL BOOM.

3. To compare residue levels and dissipation rates of glyphosate and AMPA in water, stream bottom sediment and suspended sediment, of buffered and directly sprayed streams during fall and winter storm events.

4. To assess the long term (1 year) potential for stream contamination resulting from lateral movement and mass transfer in four streams typical of a coastal forest watershed.

5. To evaluate the effectiveness of a 10-m vegetation buffer in protecting forest streams from contamination via off-target drift resulting from applications with a MICROFOIL BOOM.

## MATERIALS AND METHODS

### Site Description

The study site was located in the Carnation Creek watershed on the west coast of Vancouver Island, British Columbia (48°50'N, 125°2'W), approximately 200 km west of Victoria (Fig. 1). Carnation Creek has been the focus of a 15-year investigation of the effects of logging on fish (Hartman 1982). The main stream and side channels support populations of coho (*Oncorhynchus kisutch* Walbum) and chum (*O. keta* Walbum) salmon.

The 10-km watershed is within a coastal hemlock and cedar ecozone (Krajina 1969). Following clear-cutting in 1975, the study area was site-prepared and planted in 1976 (Dryburg 1982). Shortly after planting, thick vegetation, dominated by salmonberry (*Rubus spectabilis* Pursh) and red alder (*Alnus rubra* Bong), covered the area (King and Oswald 1982). In September 1984, the ranges in height for salmonberry and alder were 1.5-2.5 m and 7-10 m, respectively. Weather stations and a broadcast weir (B weir) were established near the mouth of Carnation Creek to monitor precipitation and stream discharge (Fig. 1). The four tributaries involved in this study were

---

[2] Registered trademark of Union Carbide Inc., Ambler, Pennsylvania

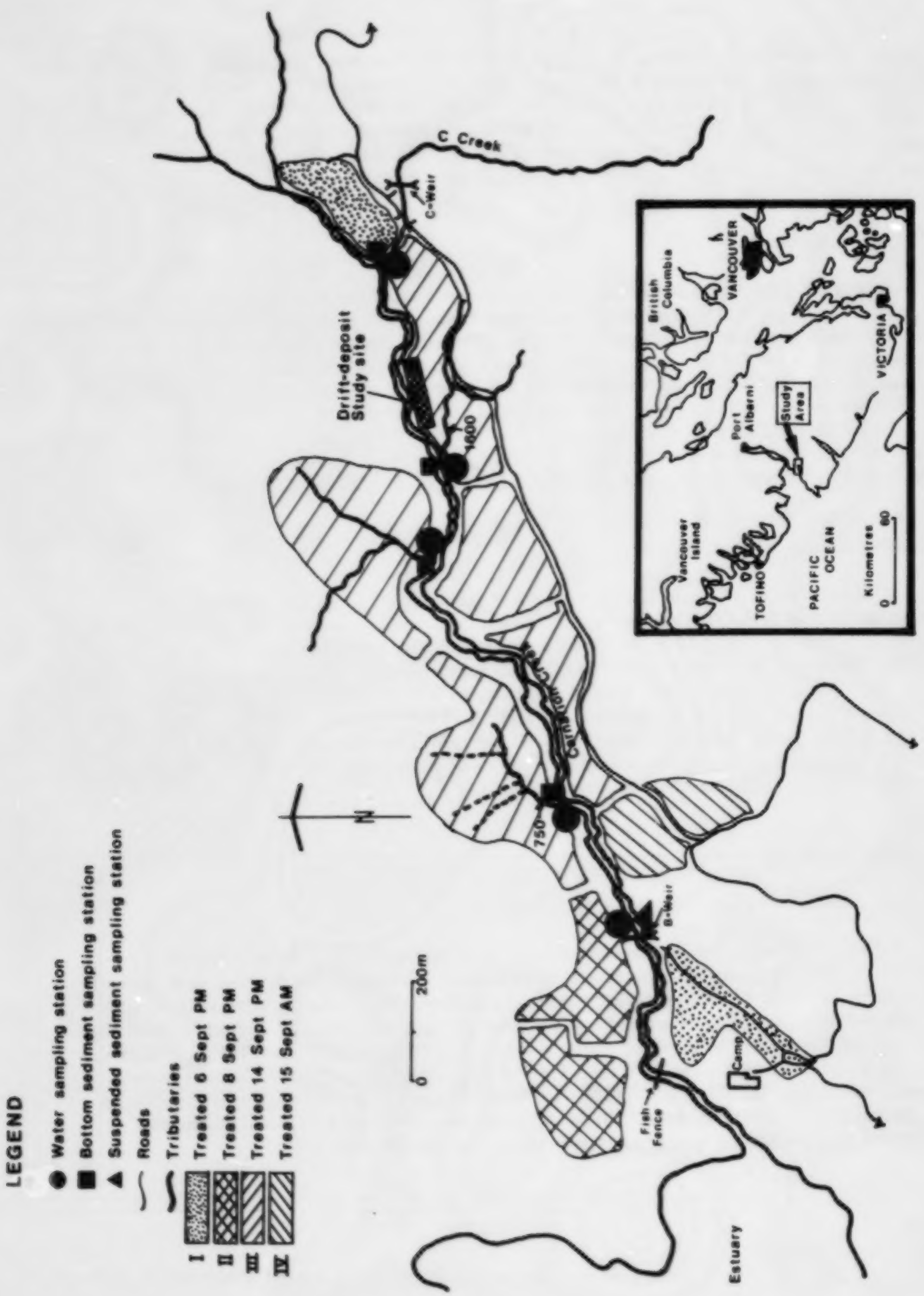

LEGEND
● Water sampling station
■ Bottom sediment sampling station
▲ Suspended sediment sampling station
Roads
Tributaries
I Treated 6 Sept PM
II Treated 8 Sept PM
III Treated 14 Sept PM
IV Treated 15 Sept AM
0 200m
N
Estuary
Fish Fence
Camp
B-Weir
750
Carnation Creek
1000
Drift-deposit Study site
C-Weir
C Creek
Vancouver Island
TOFINO
PACIFIC OCEAN
Kilometres
0 80
Port Alberni
Study Area
British Columbia
VANCOUVER
VICTORIA

Figure 1. Location of the Carnation Creek Watershed Study Area and Stream Sampling Stations.

located at 750, 1450, 1600 and 2200 m upstream from the Carnation Creek estuary; they are referred to in this manuscript as tributaries 750, 1450, 1600 and C, respectively (Fig. 1). Annual precipitation at the study site ranges from 2500 to 3800 mm and occurs mainly from October through March (Hetherington 1982). Tributaries 750, 1450 and C are ephemeral and in 1984 started flowing with the first seasonal rainfall (35 mm) on September 04. Further details regarding site characteristics and description are reported by Hartman (1982) and King and Oswald (1982).

### Herbicide Application

ROUNDUP (isopropylamine salt of glyphosate) was applied in the fall of 1984 at 2 kg active ingredient (a.i.) per hectare by a Bell-47 helicopter equipped with a MICROFOIL BOOM and 1.5-mm hayrack nozzles calibrated to deliver 258.25 L/ha. The main channel of Carnation Creek and tributaries 1450 and C (Fig. 1) were buffered with a strip of vegetation, approximately 10 m in width. Tributaries 750 and 1600 were directly treated. A total of 45 ha received herbicide application on four different days. Treatment Area I was sprayed on 06 September 1984 (1935 - 2005 h), Treatment Area II on 08 September 1984 (1416 - 1940 h), and Treatment Area III received application on 14 September 1984 (1430 - 1930 h). Meteorological conditions for specific spray periods as well as application system specifications are reported in Reynolds et al. (1989).

### Site Preparation for Deposit Study

The study area prepared for determination of initial deposit levels was located on the southern bank of Carnation Creek about 2000 m upstream from the estuary (Fig. 1). The deposit study area measured 100 x 20 m, including a vegetation-buffer strip 10 m wide by 100 m long, divided roughly in half relative to the two dominant vegetation types (salmonberry and red alder) (Fig. 2). Within the deposit-study area six transects, each 20 m apart and 20 m long, were established at right angles to the stream bank (Fig. 2). Three transect lines were located in the salmonberry area and three in the alder area. The deposit collectors were located at 5-m spacing from the stream bank at -5, 5, 10 and 15 m along each transect (Fig. 2). The outermost deposit collectors were located 5 m inside the stream channel.

### Sampling Methodologies

#### Deposit collector sampling

Deposit collectors were arranged within the off-target deposit study site as described above. In open areas, deposit collection plates (400 $cm^2$) were placed 20 cm above either ground or water level. In areas of vegetation, collectors were raised 170 cm above ground level, roughly corresponding to the height of salmonberry but below the alder tree canopy. The actual swath edge (Fig. 2) was determined by assessing phytotoxicity 10 months post-application. The swath edge was defined as the line demarcating the zone of 100% injury to salmonberry. The distances of the deposit collectors to the actual swath edge were measured and used for subsequent interpolation of glyphosate deposit at various distances from the target area. Detailed descriptions of deposit collection procedures have been reported previously (Feng and Klassen 1986).

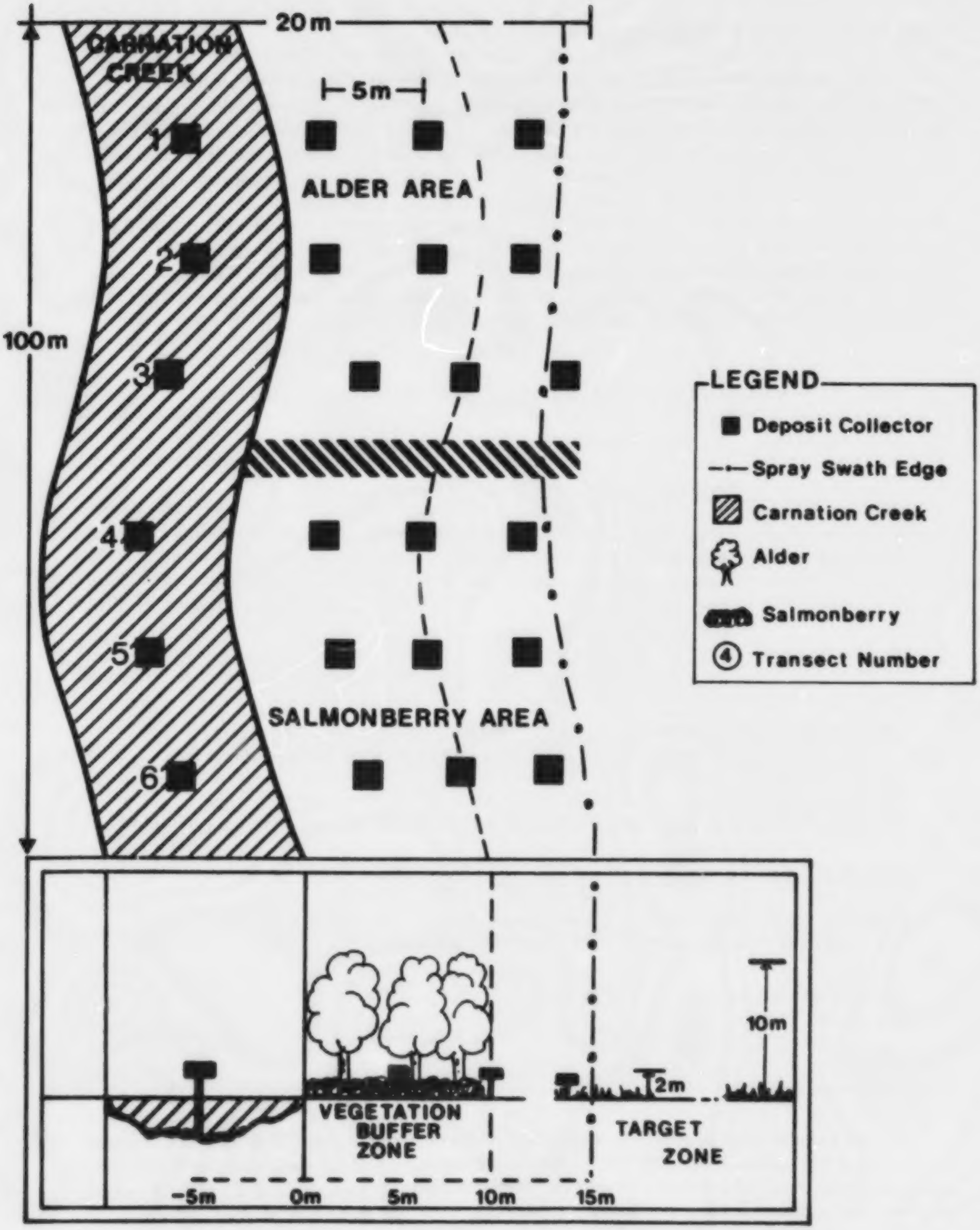

CARNATION CREEK
20m
5m
1
2
3
4
5
6
100m
ALDER AREA
SALMONBERRY AREA
LEGEND
■ Deposit Collector
Spray Swath Edge
▨ Carnation Creek
Alder
Salmonberry
④ Transect Number
10m
2m
VEGETATION BUFFER ZONE
TARGET ZONE
-5m
0m
5m
10m
15m

Figure 2. Experimental Design of the Off-Target Deposit Study at Carnation Creek Watershed.

### Initial (96-h) intensive sampling program for water residues

Water samples were collected intensively during the first 96-h period after treatment, at tributaries 750, 1450 and 1600 as well as in Carnation Creek (Fig. 1). The sampling stations for the three tributaries were located about 5 m from the confluence with the main channel of Carnation Creek. The sampling station for Carnation Creek was located at B Weir, 500 m upstream from the estuary and immediately below Treatment Area III. Water samples were collected using techniques described by Feng and Klassen (1986). The sampling protocol involved an initial, short-term, intensive sampling period during which integrated samples were collected hourly for the first 96 hours post treatment (Table 1). Integrated samples (IS) were obtained initially by collecting six samples of 150 mL at 10-minute intervals, thus yielding an hourly integrated sample with total volume of 900 mL. Following the intensive sampling period, point samples (PS) of 900 mL were collected according to the schedule as outlined in (Table 1).

Table 1. Sampling schedules for the Carnation Creek watershed study

| Sampling Site | Sampling Schedule (time post-application) |
|---|---|
| Intensive (96-h) Sampling Schedule For Water (Time in Hours) | |
| Carnation Creek | (IS) 0 1 2 3 4 5 6 7 8 |
| (B weir) | (PS) 11 14 20 29 30 31 32 33 48 72 96 |
| Tributary-750 | (IS) 0 1 2 3 |
| | (PS) 6 9 15 27 36 48 72 96 |
| Tributary-1450 | (IS) 0 1 2 3 4 |
| | (PS) 7 10 16 22 48 72 96 |
| Tributary-1600 | (IS) 0 1 2 3 4 5 6 7 |
| | (PS) 10 16 28 30 32 34 48 72 96 |
| Storm Event Sampling Schedule For Water, Bottom and Suspended Sediments | (Time in Days - Bold Values Denote Major Storm Events) |
| Carnation Creek (B weir), | **23** 24 **25** 27 30 33 40 47 **49** 51 53 57 **59** 60 62 |
| 750, 1600 & C tributaries | **66** 67 69 73 80 **84** 85 87 **150** 151 153 157 164 171 |
| Long Term Sampling Schedule (Water and Bottom Sediments) (Time in Days) | |
| Carnation Creek (B weir), | 196 210 224 238 252 263 280 297 311 326 |
| 750, 1600 and C tributaries | 339 355 364 |

IS = Integrated Sample
PS = Point Sample

### Storm event sampling

Water samples were collected in conjunction with major storm events at B weir in Carnation Creek, and at tributaries C, 750 and 1600. Suspended sediment samples were taken at B weir only, during and after major storm events (Table 1). Methods used to obtain suspended sediment samples are presented in detail by Feng and Klassen (1986). In brief, the technique involves collection and filtration of 20 L of water during each storm event: the residues in filtered sediments are quantified and reported on a μg/L basis. Storm event samples were obtained during a major storm event when the instantaneous discharge of Carnation Creek at B weir reached a threshold level of 7 $m^3/s$. Post-storm sampling commenced when the discharge decreased to below the same threshold, with collections at 1, 3, 7, 14 and 21 days after a storm or until a new storm began. Peak discharges were recorded in conjunction with each storm event, while daily rainfall and average discharge were measured throughout the sampling program.

### Long term sampling

Long term water and bottom sediment point samples were obtained from Carnation Creek (at B weir) and from tributaries 750, 1600 and C. The sampling schedule was biweekly, totaling thirteen sampling dates. Methods used to obtain water and sediment samples were described by Feng and Klassen (1986).

## Residue Analysis

### Formulation analysis

Samples of ROUNDUP formulation (356 g a.i./L) were collected before mixing for application and kept at ambient temperature. Quadruplicate 1 mL aliquots were serially diluted ($10^5$ X) with $KH_2PO_4$ buffer solution (mobile phase) as described in Table 2. The diluents were filtered with Millipore filter units (Millex HV, 0.45 $\mu$m) and subjected to HPLC analysis for glyphosate and AMPA, as described above and in Table 2.

Table 2. Specifications of HPLC instrumentation

| Component | Specification |
|---|---|
| HPLC System: | Varian Model 5560 Ternary HPLC. Model 8085 autosampler |
| Detector: | UV-200 variable wavelength detector set at 570 nm |
| Derivatization System: | Ninhydrin post column reactor (100°C)<br>System V Model 5000 (Varian Inc.) |
| Analytical Column: | Bio-Rad Aminex A-9 10 cm X 4.6 mm i.d. |
| Guard Column: | Bio-Rad Aminex A-9 ($K^+$ form cartridge) |
| Mobile Phase: | 0.005 M $KH_2PO_4$ buffer in 4% methanol pH = 1.9 |
| Flow Rate: | 0.5 mL/min (iso-cratic) |
| Column Temperature: | 50°C |

### Tank mix analysis

Tank-mix samples (400 mL) collected immediately prior to application to Treatment Area III were stored frozen prior to analysis. Duplicate 1 mL aliquots were diluted ($10^3$ X) in buffer solution and filtered and analyzed as described above.

### Deposit collector sample analysis

Residues of glyphosate and AMPA were extracted from the deposit collecting sheet by a multiple rinsing/shaking and sonicating procedure using 0.1 N HCl as the extraction solvent (Feng and Klassen 1986). The extracts were then subjected to cation and anion exchange column cleanup prior to quantification by HPLC analysis (Table 2). Herbicide quantities (glyphosate plus AMPA as glyphosate equivalent) on the deposit plates, were converted to kg/ha rates using the equation:

$$\text{kg/ha} = 2.5 \text{ X } 10^{-4} \text{ X } R$$

where R = total residue ($\mu$g) per deposit collector (400 $cm^2$). The off-target deposit residue data were subjected to linear regression analysis, using the logarithms of distance off-target in meters (X) and rate (kg/ha) of glyphosate deposited (Y) for both conditions (alder area and salmonberry area) and for the pooled data of the six replicates ($\log Y = a + b(\log X)$). Statistical differences between regression lines were determined by means of t-tests, comparing slopes (b) and elevations (a) of the lines as described by Zar (1984). Regression equations were used to interpolate distances at which deposit estimates were equal to 10, 1 and 0.1% of full deposit in the target area. Since deposit estimates were measured over a limited distance, and since distance to off-target deposit relationships are generally exponentially related over larger distances, regression equations could not be used for extrapolation beyond the furthest distance at which deposits were empirically determined. The regression equations developed to interpolate off-target deposit are specific for the application, meteorological and physical conditions of the Carnation Creek site. Since this off-target deposit study was conducted once only and conditions are not representative of worst-case scenarios, regression equations are neither accurate or useful models for purposes of prediction or establishment of buffer zone requirements.

### Water samples

Frozen water samples were thawed, acidified with HCl to pH 2 and filtered through a Millipore filtering apparatus (0.45 $\mu$m HA disc filters), prior to concentration of the analytes on cation exchange resin (Chelex, $Fe^{+++}$ form) and subsequent cleanup on anion exchange resin (AG1-X8, $HCO_3^-$ form). Extraction and cleanup procedures based on those of Cowell et al. (1986) were used, with slight modification to provide samples for HPLC analysis. The cleanup procedure was altered by increasing the concentration (6.0 to 6.5 N) of HCl used to elute the analytes from the cation exchange column. An additional modification involved final recovery of glyphosate and AMPA using mobile phase solution (as described in Table 2) rather than distilled water.

### Bottom and suspended sediment sample analysis

Residues of glyphosate and AMPA in bottom and suspended sediments were quantified using the method as described by Thompson et al. (1989). The method involves extraction of the substrate with 0.5 M $NH_4OH$, pre-concentration on AG1-X8 ($HCO_3^-$ form) anion exchange resin, cleanup via cation exchange (Dowex 50W-X8, $H^+$ form) and HPLC analysis as described below and in Table 2.

For bottom sediment samples, aliquots (20 g, air dry mass) were taken for analysis. Percent moisture was determined in duplicate aliquots for each sample so that residue levels could be calculated on μg/g dry mass basis. For suspended sediment samples the entire sample (including filter paper), as obtained from the field was weighed, homogenized and extracted. Residue results were calculated as μg/L of filtered water.

### High performance liquid chromatography

High Performance Liquid Chromatography (HPLC) coupled with post-column ninhydrin derivatization and absorbance detection (specifications as listed in Table 2) was utilized for separation and quantification of glyphosate and AMPA. Use of the short (10 cm) analytical column resulted in short retention times (7 min), improved peak shape and increased sensitivity compared to systems employing a longer (30 cm) column (Cowell *et al*. 1986).

### Validation data for analytical methods

Data indicating the accuracy and precision of analytical methods used for quantification of glyphosate and AMPA are presented in Table 3 for each substrate.

Table 3. Validation data for analytical methods

| Substrate Type | Fortification Level | N | Analyte | Mean ± s.e. (cv%) | LOD[a] (ppm)[3] | LOQ[b] (ppm)[c] |
|---|---|---|---|---|---|---|
| Deposit Collector[d] | | | | | | |
| Water | 1.0-40.0 μg/L | 25 | GLYPH | 99 ± x.x (5.0) | 0.10 | 1.00 |
| | | | AMPA | | | |
| Bottom Sediment | 0.05-0.8 μg/g | 36 | GLYPH | 79.7 ± 6.3 (7.9) | 0.03 | 0.10 |
| | | | AMPA | 64.0 ± 10.1 (15.4) | 0.01 | 0.03 |
| Suspended Sediment | 0.50-4.0 μg | 14 | GLYPH | 65.5 ± 9.1 (13.9) | 0.03 | 0.10 |
| | | | AMPA | 54.3 ± 8.5 (15.7) | 0.01 | 0.03 |

[a] LOD = limits of detection = detector response equivalent to 2X S:N ratio.

[b] LOQ = limits of quantification = detector response 6X S:N ratio.

[c] ppm = mg/L for fomulation, tank mix and water  
= mg/kg dry mass for bottom and suspended sediments.

[d] LOD and LOQ values for deposit collectors equate to 2.5 X $10^{-5}$ and 1.25 X $10^{-4}$ kg/ha respectively.

## RESULTS AND DISCUSSION

### Formulation Analysis

Analyses of the ROUNDUP formulation used for the herbicide application in this study indicated that the amount of active ingredient (glyphosate) was 363 g/L ± 2% cv, approximately 2%

in excess of the label concentration (356 g/L). No AMPA was detected in the formulation, which had been stored at ambient temperature for 3 months.

### Tank Mix Analysis

Results of the analyses conducted on the tank mix showed concentrations of 7889 and 58 $\mu$g/L of glyphosate and AMPA respectively. There was a 6% v/v contamination of the tank-mix from a six-day old mixture used to spray adjacent areas of the watershed. The amount of AMPA detected (0.7% of glyphosate concentration in the tank mix), indicated a 13% degradation of glyphosate in the previous mixture after six days of storage at ambient temperature. The initial concentration of the tank mix was corrected by converting the AMPA concentration to a glyphosate equivalence. The corrected value was 103% of the concentration required to yield an application rate of 2 kg a.i/ha.

### Off-Target Deposit Study Results

Analysis of 20 deposit collector samples indicated that the concentration of AMPA (relative to glyphosate) was 1.5%, slightly higher than the ratio for the tank mix. The highest deposit rate, which was found 2.9 m within the target area, was 1.882 kg/ha. This empirical value was 6% less than the nominal application rate for the study. The lowest quantifiable deposition rates (0.00155 and 0.000176 kg/ha) were found 17.2 and 23.1 m off-target for the salmonberry and alder areas respectively (Table 4).

Table 4. Off-target deposit of glyphosate monitored at Carnation Creek watershed

| Alder Area | | Salmonberry Area | |
|---|---|---|---|
| Distance (m) off-Target | Glyphosate deposit (kg/ha) | Distance (m) Off-Target | Glyphosate deposit (kg/ha) |
| -2.9 | 1.8820 | 1.0 | 0.1786 |
| 0.2 | 1.5093 | 2.6 | 0.01687 |
| 2.1 | 0.01934 | 3.0 | 0.02096 |
| 2.8 | 0.01025 | 6.2 | 0.00383 |
| 7.2 | 0.00239 | 6.5 | 0.00145 |
| 7.8 | 0.000364 | 11.1 | 0.00162 |
| 10.0 | 0.00115 | 12.0 | 0.000281 |
| 12.9 | 0.000337 | 13.1 | 0.000351 |
| 17.2 | 0.00155 | 21.1 | 0.000600 |
| 20.0 | <0.000025 | 22.0 | <0.000216 |
| 22.9 | <0.000025 | 23.1 | <0.000176 |

Note: Limit of detection (L O D) = 0.000025 Kg/ha
Limit of quantification (L O Q) = 0.000125 Kg/ha.

Statistical analysis of the deposit data indicated a significant ($P < 0.05$) correlation between the log of glyphosate deposited and the log of distance off-target. Linear regression on log-log transformed data yielded correlation coefficients of -0.95, -0.97 and -0.95 for the mean data values of 3 replicate transects in the alder, salmonberry and for the pooled data, respectively. The corresponding regression equations accounted for 89%, 94%, and 91% of the variation within the data, respectively. Non-significance in differences between regression lines for the salmonberry and alder areas allowed calculation of a general extinction rate from pooled data. The general extinction rate was used to estimate distance downwind from the spray boundary at which 10%, 1% and 0.1% of the full deposit would be found (Table 5). The results show a very rapid decline in glyphosate deposit with increasing distance off-target.

Table 5. Glyphosate distance:deposit relationships as calculated for the Carnation Creek study site.

| Calculated Distance Off-Target (m) | | Estimated Deposit Rate | |
|---|---|---|---|
| Alder Area | Salmonberry Area | (Kg/ha) | (% of Full Rate) |
| 0.2 | 0.3 | 2.0 | 100 |
| 0.6 | 0.9 | 0.2 | 10 |
| 2.0 | 2.7 | 0.02 | 1 |
| 7.2 | 7.8 | 0.002 | 0.1 |

Note: Off-target deposit estimates as shown in Table 5. were interpolated using the regression equations:

Alder: Log Y = a + b (log X); $r^2 = 0.89$
where: X = distance off-target (m)
Y = amount of glyphosate deposited on collectors (kg/ha)
a = -1.17
b = -1.82

Salmonberry: Log Y = a + b (log X); $r^2 = 0.94$
where: X = distance off-target (m)
Y = amount of glyphosate deposited on collectors (kg/ha)
a = -0.82
b = -2.13

Vegetation assessment indicated the average off-target distance between spray boundary and zone of 100% healthy salmonberry was 2 m. However, several pockets of partially damaged salmonberry were found up to 5 m from the spray boundary in association with scattered clumps of alder. Results of the vegetation assessment indicated that deposit rates of <0.02 kg/ha (i.e., approximately 0.01% of full application rate) would be required to ensure no phytotoxicity to salmonberry.

## Dissipation of Glyphosate and AMPA in Stream Water and Sediments

### Results of short-term intensive sampling program

Initial residue response differed in buffered and unbuffered streams. Rainfall (39 mm) occurred one day after treatment of Treatment Area III and lasted for 8 h. In streams receiving direct application, stream response was characterized by rapid decrease in residue concentrations. both immediately post-application and in response to the rainfall.

Direct treatment of tributary 750 resulted in quantifiable glyphosate concentrations (1.5 μg/L) at 1 and 2 h post-application (Fig 3). Glyphosate concentrations rose to 144 μg/L at 27 h post-application in response to the rainfall event and decreased rapidly to 2.2. 1.3 μg/L and non-detectable levels at 36, 72 and 96 h post-application, respectively. Tributary 750 was a small, ephemeral stream covered by riparian vegetation for most of its length. At the time of application it exhibited a slow flow rate (0.001 $m^3$/s). As compared to the inital stream response to direct over-spray, longer periods of time (>45 h vs. <5h) were required for residues to dissipate below detectable levels. The 100-fold increase in concentrations of glyphosate in stream water following the first rainfall event may have been the result of several sources of input including mobilization of residues in ephemeral stream channels feeding the tributary (Norris et al. 1983), washing of residues from leaves of overhanging vegetation, surface movement and subsurface flow. Norris et al. (1983) noted that mobilization of residues in runoff may yield longer lasting effects than direct application. In a study of agricultural watersheds, Edwards et al. (1980) showed that residues of glyphosate were transported mainly via overland (surface) runoff, rather than through subsurface flow.

Tributary 1600 received direct chemical application for about 600 m of its 800 m length. At the time of application the stream was fast flowing (0.02 $m^3$/s) and contained pools ranging from 0.5 to 1 m in depth. Stream banks were covered with salmonberry and alder vegetation. Residues were detected in water samples immediately following direct deposit of glyphosate, concentrations peaked at 162 μg/L within 2 h and decreased rapidly to 54.4 and 36.5 μg/L at 7 and 16 h, respectively (Fig. 3). The magnitude of the initial concentrations and rate of residue dissipation in this stream were comparable to those observed in a similar forest stream in Oregon (Newton et al. 1984). Following the first rainfall, concentrations of glyphosate in the water rose to 109 μg/L at 28 h and decreased rapidly thereafter to 1.3 μg/L at 96 h (Fig. 3). Concentrations of AMPA found in both tributaries 750 and 1600 were about 2% of corresponding glyphosate concentrations.

The buffered tributary 1450 was selected to represent a worst-case situation for operational spraying and to determine the accuracy of aerial application while maintaining a designated buffer without an intensive boundary marking system. This tributary consisted of a network of branching stream channels, mid-portions of which either flowed underground or were covered with dense 2 m high salmonberry. The stream boundary of these sections could not be clearly identified from the air. About two-thirds of its length (600-800 m) were adjacent to Treatment Area III (Fig. 1). Stream flow at the time of application was 0.01 $m^3$/s. No quantifiable residues were found in the first 7 h of the intensive sampling program. The rainfall that occurred at 20 to 28 h post application did not mobilize significant quantities of glyphosate into this stream during the first 16 to 96 h post-application. These results indicate that a 10-m wide vegetation buffer is adequate to prevent stream contamination from either direct aerial application, drift or from subsequent inputs in the first 96 h. One anomalous sample (10 h post-application) was identified, having a concentration of 2.5 μg/L of glyphosate. This delayed response may be the result of an accidental spray over a middle section of the tributary, which eventually flowed underground. The slower water velocity, which would be expected in subterranean flow, may be responsible for the delay of residue response to 10 h post application.

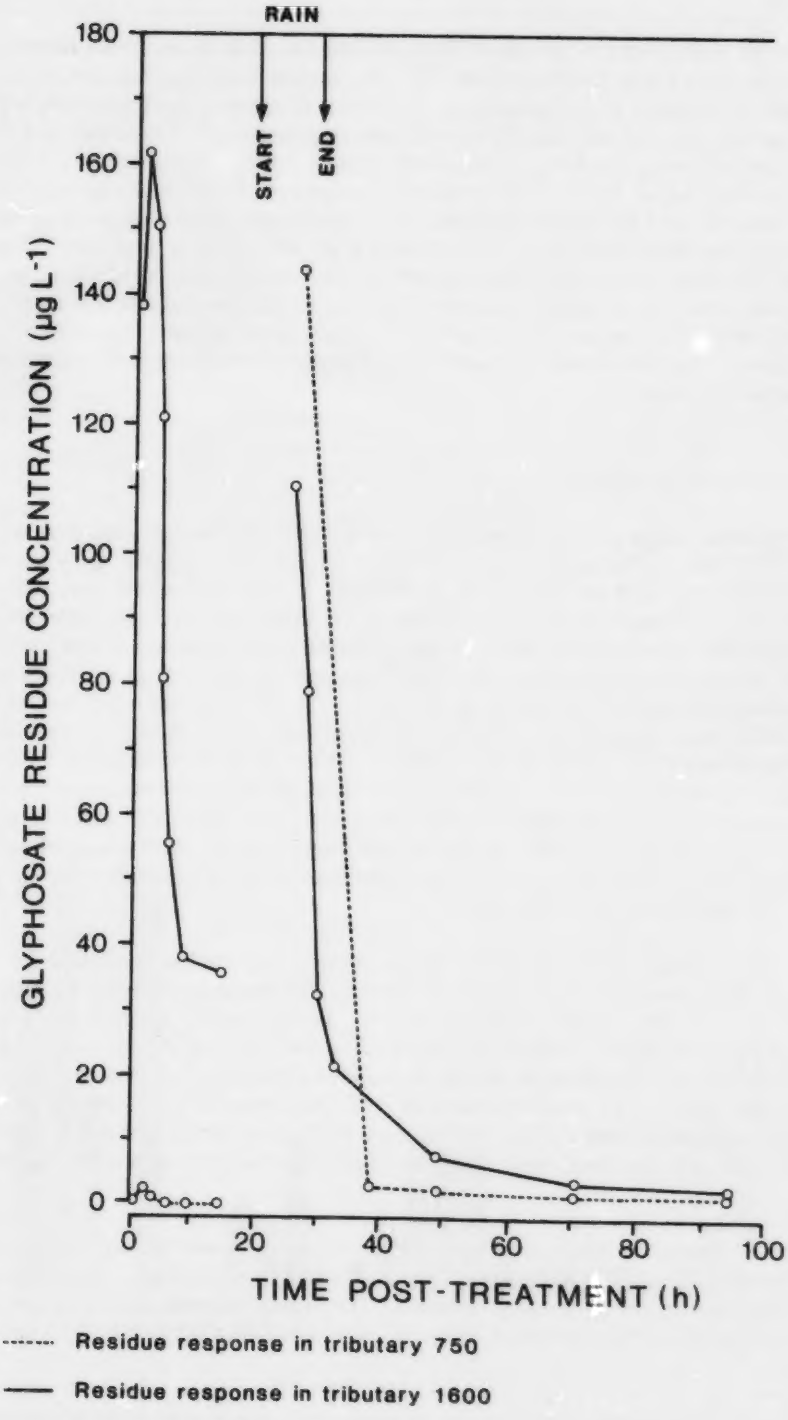


Figure 3. Short-term Streamwater Residues of Glyphosate in Carnation Creek Watershed Tributaries 750 and 1600.

The buffered main stream (Carnation Creek) was monitored at B weir, both following application to Treatment Area I and Treatment Area III. No residues were found in any of the 12 samples collected after application to Treatment Area I. Results of samples associated with application to Treatment Area III, showed that the main stream responded with quantifiable glyphosate concentrations only following the direct treatment of tributary 1600. Glyphosate (1-1.5 μg/L) was found in only two samples, 4 and 6 h after treatment. In general, these results corroborate other studies, which indicate rapid dissipation of glyphosate in both lentic surface waters (Legris et al. 1985) and lotic systems (Comes et al. 1976; Norris et al. 1983; Legris et al. 1985). In lotic systems such as Carnation Creek, this effect may be the result of degradation, dilution, adsorption to organic substrates or uptake by biota. Glyphosate concentrations in five samples collected between 29 and 33 h rose to 1.7-3.2 μg/L in response to the rainfall. The 2-fold increase in main stream water residues further indicated input of chemical from non-point sources such as charged ephemeral tributaries.

## Results of Storm Event Monitoring

During the observation period, seven storm events above 3 $m^3$/s were identified as major storms (Table 1.). Stream discharges monitored in Carnation Creek for these seven events were: 13.1, 8.3, 10.0, 5.3, 3.0, 4.0, and 4.4 $m^3$/s, respectively. Cumulative rainfall was 1490 mm during this period. As a result, a total of 120 water samples (900 mL PT) were collected on 30 different days from the main channel and three tributaries (750, 1600 and C) (Table 1). No quantifiable residues of glyphosate or AMPA were found in any of the water samples. Trace amounts (< 1 μg/L) of glyphosate were detected in one sample from the main channel following storm event 7 and in one water sample from tributary 750 following the first storm event. Similarly, transient indications of trace residues were observed in tributary 1600 in five of seven major storm events (i.e. on days 23, 25, 49, 59 and 150 post-application). Glyphosate concentrations observed 23 days after treatment were approximately 1000-fold lower than those found after the rainfall (39 mm) event 27 h post-application. These results are consistent with the observations of other workers (Kimmins 1975; Edwards et al. 1980), that the first rainfall after treatment generates the highest residue concentrations in stream water.

A total of 120 samples of stream bottom sediments were collected in conjunction with storm events. No quantifiable amounts of glyphosate or AMPA were found in the buffered tributary C and main channel during the storm-event monitoring period. In the directly treated Tributaries 750 and 1600, glyphosate and AMPA residues in bottom sediments persisted throughout the storm-event monitoring period (Fig.4). The highest bottom sediment concentrations of glyphosate (0.44 and 0.58 μg/g dry mass) found in tributary 750 were in conjuction with the third major storm event, 53 and 57 days post-application, respectively. In tributary 1600, peak bottom sediment concentrations (6.80 and 6.34 μg/g dry mass) were observed 24 and 30 days post-application, respectively (Fig. 4).

A total of 29 suspended sediment samples were collected at B weir during 8 storm events that occurred between 23 and 171 days post-treatment (Table 1). Quantifiable glyphosate residues were found in only four of the 29 samples collected. The highest concentrations detected in suspended sediments (0.060 μg/L) occurred in conjunction with the first storm event, 23 days post-application.

Monitoring in conjunction with major storm events indicated that residues of glyphosate and AMPA are associated primarily with bottom sediments, with no quantifiable residues being observed in stream water. Highest concentrations were found in the slow-flowing tributary 1600, which meanders through the floodplain, while the swift-flowing 750 tributary had much lower con-

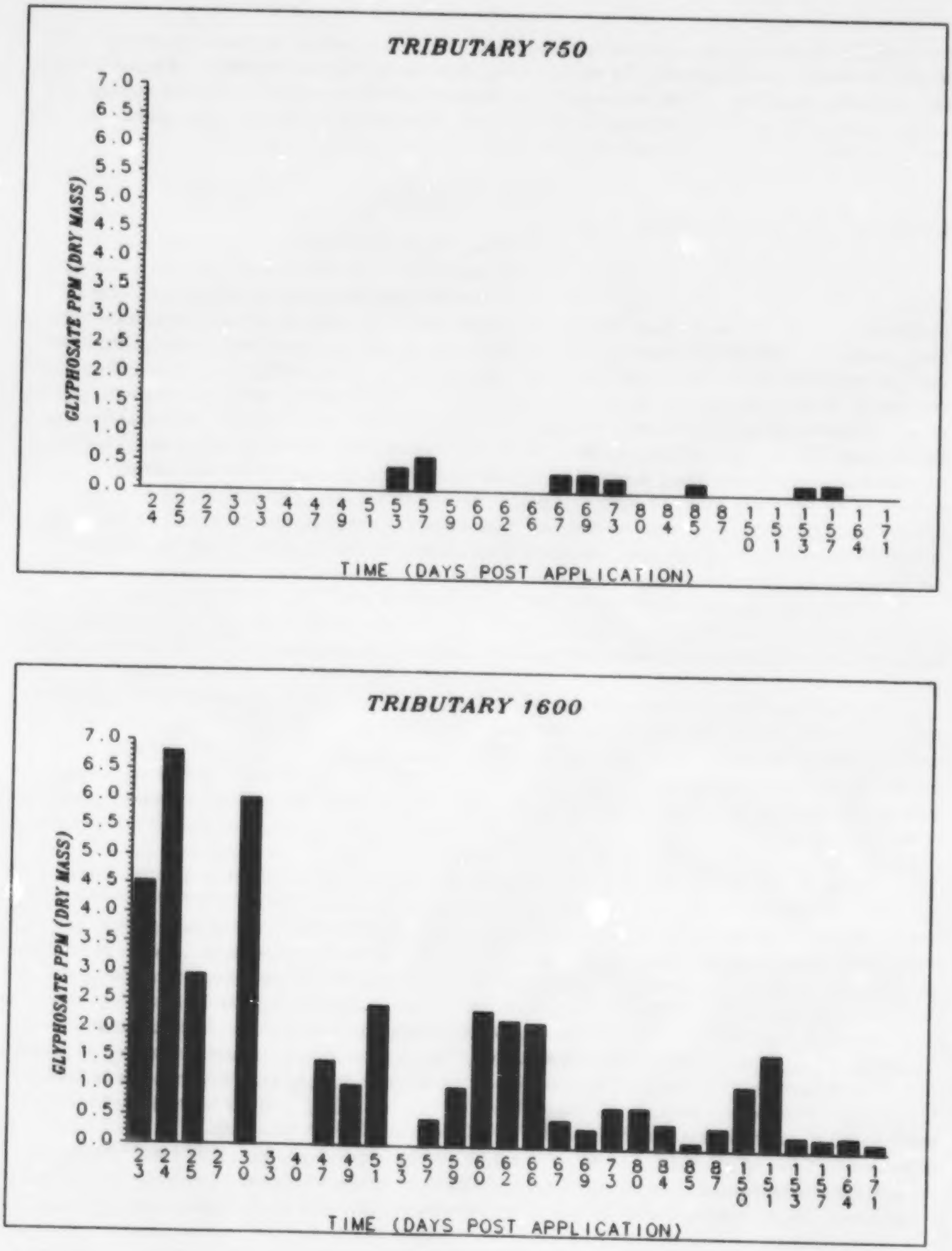


**Figure 4. Residues of glyphosate in bottom sediments of directly oversprayed tributaries at Carnation Creek, British Columbia.**

centrations. Levels of glyphosate residue associated with bottom sediments appear to depend largely on stream flow dynamics. In slow-flowing, meandering streams deposition of contaminated sediment may result in transient increases in residue concentrations. In contrast, fast-flowing streams inherently have little sediment deposition and are regularly flushed-out during storm events, resulting in bottom sediment concentrations being somewhat lower.

### Results of Long Term Dissipation Study

Biweekly samples of both water and bottom sediments were taken from the main stream and tributaries 750, 1600 and C during the period 196 to 364 days after treatment (Table 2). No detectable residues (detection limit = 0.1 $\mu$g/L) were found in any of the 48 scheduled water samples. Analyses of 49 bottom sediment samples taken during this period showed no quantifiable residues in sediments of the Carnation Creek main channel or C-tributary (Fig. 4). Quantifiable residues (1.92 to 0.14 $\mu$g/g dry mass) were observed in bottom sediments of directly sprayed tributaries 750 and 1600 during the long term monitoring period (196-364 days post application). The data indicate that residues in bottom sediments were comparatively persistent, with levels variable but generally declining over time. By the end of the long term monitoring period, residue levels were less than 0.2 $\mu$g/g dry mass. Results of the long term monitoring program provide no evidence of glyphosate or AMPA accumulation in either bottom sediments or water and no quantifiable residues in stream water resulting from inputs via mass transfer or lateral movement mechanisms.

### Relationship of Observed Residue Concentrations to Toxicological Data

Application of glyphosate to the Carnation Creek Watershed approximates a worst-case scenario for the silvicultural use of this herbicide. As would be expected, the highest residue concentrations were observed in water samples taken immediately after direct application to tributaries 750 and 1600. Residues dissipated rapidly from water and tended to be sorbed by bottom sediments. No evidence of accumulation of glyphosate or its metabolite AMPA in sediments was observed.

Although it is beyond the scope of this paper to draw absolute conclusions regarding the potential for aquatic impacts as a result of silvicultural applications of ROUNDUP, it is of interest to compare actual environmental concentrations of glyphosate observed in this study with those concentrations of the active ingredient known to elicit acute toxic response. Servizi et al. (1987) have recently reported on the acute toxicity of ROUNDUP, the active ingredient glyphosate and the surfactant MONO818 to four aquatic organisms including *Onchorhyncus* sp. fry. The data indicate that all four species show similar sensitivities to these materials. Mitchell and Chapman (1986) reported that environmental concentrations resulting from aerial spraying of ROUNDUP herbicide are 100-fold less than levels found to be acutely toxic to salmonids in 96 h $LC_{50}$ tests. The highest streamwater concentrations observed in this study (162 $\mu$g/L in directly oversprayed tributary 1600) is approximately 80-fold less than the 96 hour $LC_{50}$ reported for coho salmon (Wan et al. 1988), when corrected for glyphosate equivalence (30% a.e.). Similarly, the highest concentrations observed in our study were well below sub-lethal no-effect levels for coho salmon smolt osmoregulation or growth as reported by Mitchell et al. (1987).

With respect to toxicity of glyphosate to organisms other than fish, direct observation indicated that residue concentrations at B Weir and tributaries 1600 and C induced a minimum response in drift of aquatic invertebrates (Kreutzweiser and Kingsbury 1989).

Thus, the results of this study generally indicate a large safety margin between stream water concentrations of glyphosate resulting from forest applications and known acute and subacute toxicological endpoints.

## CONCLUSIONS

In relation to the objectives of the study, the following conclusions may be drawn:

a) Results of the off-target deposit collector experiment indicate that the herbicide application was reasonably accurate in that the empirical value for application rate was within 6% of the nominal rate for target area. The data also showed that use of the MICROFOIL BOOM under operational spraying conditions results in very little off-target deposit. Estimated deposit at distances greater than 8 m off-target were less than 0.1% of full application rates in this study. Results of the off-target deposit study conducted at Carnation Creek suggest that under the specific application and meteorological conditions of this study, a 10-m wide vegetation buffer zone of either salmonberry or alder, effectively protected streams from herbicide contamination following application of the herbicide ROUNDUP with a MICROFOIL BOOM.

b) Initial residue levels in stream water were correlated with a variety of factors including; stream flow rate and volume, occlusion of water surface by overhanging vegetation, and degree of input from intentional direct treatment. Directly treated tributaries contained the highest concentrations of the active ingredient, these levels were well below concentrations known to be acutely toxic to sensitive aquatic organisms. Residues in stream water dissipated rapidly, so that chemical concentrations were below detection limits (0.1 ppb) within 96 h of the application. Dissipation was more rapid in a fast flowing tributary than in a slow-flowing, meandering tributary in the floodplain.

c) Storm-event monitoring showed that no quantifiable residues of glyphosate occurred in stream water in conjunction with storm events. Bottom sediments appeared to be the major sink for glyphosate residues with high concentrations correlated to storm events. Residues associated with bottom sediments persisted throughout the monitoring period, the degree of contamination appears to be related to stream dynamics and location.

d) Results of the long-term dissipation monitoring study indicated no potential for persistence of residues of either glyphosate or AMPA in stream water. Long-term residues were associated predominantly with bottom sediments, indicating that this substrate attenuated residues from stream water by sorption processes. In contrast with the rapid dissipation of residues in stream water, sediment residues were relatively persistent. The slow rate of glyphosate degradation in bottom sediments, coupled with the known chemical behavior of glyphosate on organic substrates indicates that these residues are strongly sorbed to this substrate and thus unlikely to be biologically available.

The residue data resulting from this study support the conclusion of Tooby (1985), who stated that "...it is unlikely that glyphosate will affect aquatic organisms at the concentrations found in the environment after use at the recommended rates." Given the rapid dissipation of this chemical in forest stream ecosystems, its susceptibility to biodegradation and its tendency to sorb strongly to organic substrates, significant biological impact to aquatic organisms as the result of silvicultural applications at recommended rates would be highly unlikely.

## ACKNOWLEDGEMENTS

This research, supported under the British Columbia Forest Resource and Development Agreement (FRDA), was conducted by members of the Forest Pest Management Institute (FPMI), of the Canadian Forestry Service. Cooperation of the British Columbia Ministry of Forests, the Pacific Forestry Centre (PFC), Fisheries and Oceans Canada, MacMillan Bloedel Ltd., and Monsanto Canada Inc. were integral to the success of this project. Herbicide application was contracted to Rotor Vegetation Control (R. Rowe) and Alpine Helicopters (D. Gubbels and D. Cholka) both of Calgary Alberta. The authors sincerely appreciate and acknowledge the excellent technical assistance in residue analysis of B. Staznik, T. Buscarini, V. Manniste-Squire, and L. MacDonald (FPMI), and of H. Klassen and D. DeKoven (V.A. Poulin and Assoc. Ltd.) who performed the field sampling.

## REFERENCES

Comes, R.D., V.F. Bruns and A.D. Kelly. 1976. Residues and persistence of glyphosate in irrigation water. Weed Sci. 24(1):47-50.

Cowell, J.E., J.L. Kunstman, P.J. Nord, J.R. Steinmetz and G.R. Wilson. 1986. Validation of an analytical residue method for analysis of glyphosate and metabolite: An interlaboratory study. J. Agric. Food Chem. 34:955-960.

Dryburg, J.G. 1982. Carnation Creek logging and silvicultural treatment program. pp. 36-43 In G.F. Hartman (ed.) Proceedings of the Carnation Creek workshop, a 10-year review . February 24-26, 1982. Malaspina College, Nanaimo, B.C.

Edwards, W.M., G.B. Triplett and R.M. Kramer. 1980. A watershed study of glyphosate transport in runoff. J. Environ. Qual. 9(4):661-665.

Feng, J.C., and H.D. Klassen. 1986. Forestry field and laboratory manual for herbicide residue sampling, sample processing and reporting. Can. For. Serv., For. Pest Manage. Inst., Sault Ste. Marie, Ont. Inf. Rep. FPM-X-72.

Ghassemi, M., L. Fargo, P. Painter, S. Quinlivan, R. Scofield and A. Takata. 1981. Environmental fates and impacts of major forest use pesticides. EPA Contract No. 68-02-3174, U.S. Environ. Prot. Agency, Off. Pestic. Toxic Subst., Washington, D.C.

Hartman, G.F. 1982. [ed.]. Proceedings of the Carnation Creek workshop, a 10-year review. February 24-26, 1982. Malaspina College, Nanaimo, B.C.

Hetherington, E.D. 1982. A first look at logging effects on the hydrologic regime of Carnation Creek experimental watershed. pp. 11-15 In G.F. Hartman (ed.) Proceedings of the Carnation Creek workshop, a 10-year review. February 24-26, 1982. Malaspina College, Nanaimo, B.C.

Kimmins, J.P. 1975. Review of the ecological effects of herbicide usage in forestry environment. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-139.

King, R.K. and E.T. Oswald. 1982. Revegetation of Carnation Creek watershed. pp. 110-128 In G.F. Hartman (ed.) Proceedings of the Carnation Creek workshop, a 10-year review. February 24-26, 1982. Malaspina College, Nanaimo, B.C.

Krajina, V.J. 1969. Ecology of forest trees in British Columbia. pp. 1-146 In V. Krajina and R. Brooks (eds.) Ecology of western North America. Vol. 2, Nos. 1 and 2. Dept. Botany, Univ. B.C., Vancouver, B.C.

Kreutzweiser, D.P. and P.D. Kingsbury. 1989. Drift of aquatic invertebrates in a glyphosate contaminated watershed. This proceedings.

Legris, J., G. Couture, L. LaBerge et G. Mamarbachi. 1985. Concentrations residuelles de glyphosate dans l'eau de surface en milieu forestier suite a des pulverisations terrestres, 1985. Governement du Quebec, ministere de l'Energie et des Ressources. Service des etudes environmentales, #3315. pp. 35.

Malik, N., and W.H. Vanden Born. 1986. Use of herbicides in forest management. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-282.

Mitchell, D.G. and P.M. Chapman. 1986. Acute toxicity of Roundup herbicide to coho salmon, chinook salmon and rainbow trout. Report prepared for Monsanto Co., St. Louis, Missouri, by E.V.S. Consultants, Vancouver, B.C. (as cited in Mitchell et al. 1987).

Mitchell, D.G., P.M. Chapman and T.J. Long. 1987. Seawater challenge testing of coho salmon smolts following exposure to Roundup herbicide. Environmental Toxicology and Chemistry. 6:875-878.

Newton, M., K.M. Howard, B.R. Kelpsas, R. Danhaus, C.M. Lottman and S. Dubelman. 1984. Fate of glyphosate in an Oregon forest ecosystem. J. Agric. Food Chem. 32:1144-1151.

Norris, L.A. H.W. Lorz and S.V. Gregory. 1983. Forest chemicals. In W.R. Meehan (ed.) Influence of forest and rangeland management on anadromous fish habitat in western North America. USDA For. Serv., Gen. Tech. Rep. PNW-149.

Payne, N., J. Feng, and P. Reynolds. 1986. Off-target deposit measurement and buffers required around water for aerial glyphosate application. Can. For. Ser., For. Pest Manage. Inst., Sault Ste. Marie, Ont. Inf. Rep. FPM-X-80.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. An overview of Carnation Creek herbicide study: historical perspective, experimental protocols, and spray operations. This proceedings.

Rueppel, M.L., B.B. Brightwell, J. Schaefer and J.T. Marvel. 1977. Metabolism and degradation of glyphosate in soil and water. J. Agric. Food Chem. 25:517-528.

Servizi, J.A., R.W. Gordon and D.W. Martens. 1987. Acute toxicity of GARLON 4 and ROUNDUP herbicides to Salmon, Daphnia, and Trout. Bull. Env. Contam. Toxicol. 39:15-22.

Thompson, D.G., B.J.E. Cowell, R.J. Daniels, B. Staznik and L. MacDonald. 1988. An alternative method for quantification of glyphosate and AMPA residues in organic and mineral soils, stream sediments and hardwood foliage. J. Assoc. Off. Anal. Chem. (in press).

Tooby, T.E. 1985. Fate and biological consequences of glyphosate in the aquatic environment. pages 206-217 In E. Grossbard and D. Atkinson (eds.) The Herbicide Glyphosate. Butterworths, London, U.K.

Wan, M.T. et al. 1988. Toxicity of the herbicide glyphosate (ROUNDUP) and its surfactant to salmonids. p. 41 In Environment Canada-Pesticides Research and Monitoring Annual Report: 1986-87. Ministry of Supply and Services, Canada.

Zar, J.H. 1984. Biostatistical analysis. 2nd edition. Prentice-Hall, Inc., Englewood Cliffs, N.J. pp. 292-298.

# PERSISTENCE AND DISSIPATION OF GLYPHOSATE IN FOLIAGE AND SOILS OF A CANADIAN COASTAL FOREST WATERSHED

Joseph C. Feng[1] and Dean G. Thompson[2]

[1]Northern Forestry Centre
Canadian Forestry Service
5320-122nd Street
Edmonton, Alberta T6H 3S5

[2]Forest Pest Management Institute
Canadian Forestry Service
P.O. Box 490
Sault Ste. Marie, Ontario P6A 5M7

## ABSTRACT

The environmental persistence and behavior of glyphosate and its major metabolite - aminomethylphosphonic acid (AMPA), were investigated in terrestrial components of a Canadian coastal forest watershed, following aerial application of ROUNDUP herbicide. The uniformity of herbicide deposition resulting from rotary-wing application with a MICROFOIL BOOM was assessed through analyses of deposit collectors and initial soil residues at three sampling sites located in the upper, middle and lower sections of the watershed. Samples of soil from three depth-layers were analyzed to determine the persistence and leaching of glyphosate and AMPA in both seasonally flooded and well-drained soils. In addition, foliage and leaf litter of two brush species, salmonberry (*Rubus spectabilis*) and red alder (*Alnus rubra* Bong) were monitored to determine initial foliage residue, residues associated with leaf litter and to estimate the degree of residue input via leaf fall.

Both the deposit collector and soil residue methods provided average estimates of initial deposit rates (2.52 and 1.85 kg/ha, respectively), which were reasonably close to the nominal application rate of 2.0 kg/ha. Both data sets also indicated that deposition rates varied greatly between different sites, ranging from a low of 0.60 kg/ha to a high of 3.42 kg/ha. Time of application, meteorological conditions and individual site characteristics may all have contributed to variable chemical deposit.

Analyses of initial foliage samples also indicated highly variable chemical deposition. Residue levels in both salmonberry and leaf litter collected 15 days post-application were significantly lower ($P > 0.05$) than initial foliage residues. Subsequently, leaf litter residues of glyphosate and AMPA in both species declined over time and less than 1% remained 29 days post-application. The significant difference between initial foliage residues and the first leaf litter residues was attributed to wash-off resulting from a rainfall event which occurred 1 day post-application. The results indicate that while leaf-litter residues would be an unimportant transient source of chemical contamination, wash-off of unabsorbed foliage residues may provide an important non-point source input, if rainfall occurs shortly after application.

Soil residue determinations showed that both glyphosate and AMPA were retained primarily in the upper, organic-rich soil layer, 0-15 cm. Of 63 determinations of mean glyphosate distribution, only 10 data points indicated greater than 10% of total soil core residue in the 15-30 cm layer. No quantifiable residues were detected in samples taken from the 30-35 cm layer. Residues of glyphosate declined with time at all locations so that only 6-18% of initial levels remained after 360 days. Declining glyphosate residues coupled with transient increases in AMPA residues were indicative of microbial degradation. Insufficient replication, high variability in soil residues and site location effects on chemical behavior prohibited accurate derivation of persistence endpoints by regression analysis. However, pooling of the data provided an approximate time to 50% dissipation of glyphosate from watershed soils of 45-60 days. The results of this one-year monitoring study indicate that glyphosate and its major metabolite AMPA are non-persistent in terrestrial components (soil and leaf-litter) of a Canadian coastal rainforest watershed. In addition, the data clearly showed that neither glyphosate nor AMPA are susceptible to leaching under the conditions studied. The data provide no evidence of potential for long-term groundwater or surface water contamination as a result of inputs from terrestrial substrates.

## INTRODUCTION

The herbicide ROUNDUP[1] (active ingredient - glyphosate), received federal registration for silvicultural use in 1984. Since that time, use of this chemical in Canada has been steadily increasing. The environmental fate and persistence of glyphosate in soils has been extensively investigated by a number of researchers (Rueppel et al. 1977; Edwards et al. 1980; Hance 1976; Sprankle et al. 1975; Muller et al. 1981; Moshier and Penner 1976). However, the majority of this research has been conducted in the United States and pertains primarily to persistence and adsorption in agricultural soils. The environmental behavior of glyphosate in other terrestrial ecosystems has been less thoroughly studied. Newton et al. (1984) and Torstensson and Stark (1981), have both reported on the fate and behavior of glyphosate in forest soils: both studies indicating that glyphosate is relatively non-persistent. Torstensson (1985) indicated that the persistence of glyphosate in soils is affected by a multiplicity of factors that mediate microbial activity, the primary mechanism by which this herbicide is degraded.

In the coastal area of British Columbia, typical climatic conditions include frequent autumn and winter rainstorms with annual rainfall often exceeding 2000 mm annually. The results of such a precipitation pattern are: areas of high water table, seasonally saturated soils and frequent surface runoff events following major storms. Typically, soil profiles in the floodplain of coastal forest watersheds are highly stratified into organic-rich (30% or greater organic matter content) upper horizons, underlain by coarse-textured mineral soils, low in organic matter. Thus, from a purely physical standpoint, terrestrial forest ecosystems are vastly different than the more homogeneous agricultural soil systems that are traditionally studied. The potential for vertical leaching, loss through surface runoff and persistence of glyphosate under such soil and climatic conditions is unknown.

A relatively large amount of information is available with respect to the fate and behavior of glyphosate in plants. However, most of these studies have been conducted on agricultural crops or specific weed species, which may have little relevance to typical crop and weed species in forest environments. Newton et al. (1984) monitored the persistence of glyphosate in red alder (*Alnus rubra* Bong.) and other forest hardwood species. Lund-Hoie (1976) reported on the uptake, distribution and metabolism of this herbicide in spruce (*Picea abies*) and later in two brush species - ash (*Fraxinus excelsior*) and birch (*Betula verrucosa*) (Lund-Hoie 1979). Putnam (1976) studied the translocation and persistence of glyphosate in various deciduous fruit tree species following basal bark applications. During aerial application of herbicides, chemical is intercepted primarily by the broadleaf-target species. The herbicide may persist in or on the leaf tissue until senescence and leaf fall during autumn. In this way, chemical may be transported to the forest floor in the form of leaf-litter residue. The degree to which foliar interception and deposition (via subsequent leaf fall) occurs has not been adequately quantified.

---

[1] Registered trademark of Monsanto Agricultural Products Co., St. Louis, Missouri.

Although an extensive data base exists with respect to the environmental fate and behavior of glyphosate in terrestrial ecosystems, little is pertinent to the conditions typical of the western coastal forest region where glyphosate receives widespread use for conifer release and site preparation. Federal and provincial regulatory agencies require further information on the fate and persistence of glyphosate relevant to its operational use under local geological and climatic conditions.

The research described in the following manuscript was undertaken to provide data relevant to the concerns of federal and regional regulatory agencies in Canada and to address questions that are inadequately dealt with in the current literature.

The specific objectives of the study were:

a) To assess the uniformity of deposition of glyphosate following a rotary-wing, aerial application with a MICROFOIL BOOM [2], under near-operational conditions in a coastal British Columbia watershed.

b) To monitor the persistence of glyphosate and its major degradation product, AMPA, in both well-drained and seasonally flooded soils over a one year period following aerial application.

c) To determine the leaching potential of glyphosate and AMPA in soil systems typical of a coastal British Columbia watershed.

d) To determine the initial residue levels associated with the major target species and to monitor the degree to which residues are transported to the forest floor as leaf-litter residue.

## MATERIALS AND METHODS

### Site Description

The experimental study site is located in the Carnation Creek watershed on the west coast of Vancouver Island, British Columbia (48°50'N, 125°2'W), about 200 km west of Victoria (Fig. 1). The 10-km watershed is within a coastal hemlock and cedar ecozone (Krajina 1969). Annual precipitation ranges from 2500 to 3800 mm and occurs primarily from October through March (Hetherington 1982). The study site was clear-cut in 1975 and site-prepared and planted in 1976 (Dryburg 1982). At the time of chemical application (September 1984), thick vegetation dominated by salmonberry (*Rubus spectabilis* Pursh) and red alder (*Alnus rubra* Bong.) covered the area, ranging in height from 1.5-2.5 m and 7-10 m respectively. Characteristics of soils within the watershed (Table 1) were determined from samples taken immediately prior to herbicide application.

### Site Preparation

Three soil sampling sites were chosen within the watershed as indicated in Figure 1 and Table 2. Soil sites were selected in both the upper (stations 1-3) and lower (stations 7-9) sections of the watershed to monitor persistence and leaching in well-drained soils. The mid-watershed soil site (stations 4-6) was established in a low-lying area known to be seasonally flooded. At each site, three 5 x 5 m areas were cleared by removing above-ground vegetation.

---

[2] Registered trademark of Union Carbide Inc., Ambler, Pennsylvania.

Table 1. Soil characteristics of the Carnation Creek Watershed study site

| Soil Depth (cm) | O.M. (%) | CEC | N (%) | P (ppm) | K (%) | pH | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|---|---|---|
| Stations 1-3 | | | | | | | | | |
| 0-5 | 30.39 | 45.85 | 0.60 | 17.05 | 0.03 | 4.94 | 55.85 | 23.70 | 20.46 |
| 5-15 | 19.47 | 51.33 | 0.50 | 15.18 | 0.02 | 4.55 | 55.79 | 23.73 | 20.48 |
| 15-35 | 9.28 | 26.37 | 0.21 | 1.47 | 0.01 | 5.28 | 62.01 | 17.50 | 20.49 |
| Stations 7-9 | | | | | | | | | |
| 0-5 | 30.90 | 50.47 | 0.12 | 54.04 | 0.03 | 4.49 | 62.02 | 24.99 | 12.99 |
| 5-15 | 14.88 | 48.13 | 0.84 | 10.55 | 0.02 | 4.20 | 54.68 | 24.90 | 20.42 |
| 15-35 | 10.21 | 27.44 | 0.07 | 1.03 | 0.01 | 4.65 | 65.80 | 16.23 | 17.97 |

C E C = Cation exchange capacity            OM = Organic matter
N = Nitrogen            P = Phosphorous            K = Potassium

Table 2. Herbicide application data for the Carnation Creek Watershed study site**

| Sampling stations | Application specifics | | | Treatment area[+] |
|---|---|---|---|---|
| | Date | Time | Nominal rate kg/ha | |
| Soil (1,2,3)<br>Leaf-litter (A-1*) | 06-09-84 | 1935-2005 | 2.0 | I |
| Soil (4,5,6)<br>Leaf-litter (S-1*) | 14-09-84 | 1430-1539 | 2.1 | III |
| Leaf-litter (A-2,S-2*) | 14-09-84 | 1730-1814 | 2.1 | III |
| Soil (7,8,9) | 06-09-84 | 1900-1925 | 2.0 | I |

* A-1/A-2 = Alder - stations 1 and 2, respectively.
S-1/S-2 = Salmonberry - stations 1 and 2, respectively
** Reynolds _et al_. 1989
[+] Treatment areas as shown in Figure 1.

large debris and slash, with minimal disturbance to the forest floor. Three replicate sampling stations were created. At each site, a total of eight deposit plates, each with a surface area of 400 $cm^2$, were placed around the periphery of the sampling stations. The deposit collectors were used to provide an estimate of the initial residue deposited on the soil surface and to allow assessment of the uniformity of chemical application using the MICROFOIL BOOM.

Duplicate leaf-litter sampling stations were established in each of two separate areas dominated by salmonberry and red alder respectively (Fig. 1 and Table 2). Sampling plots for

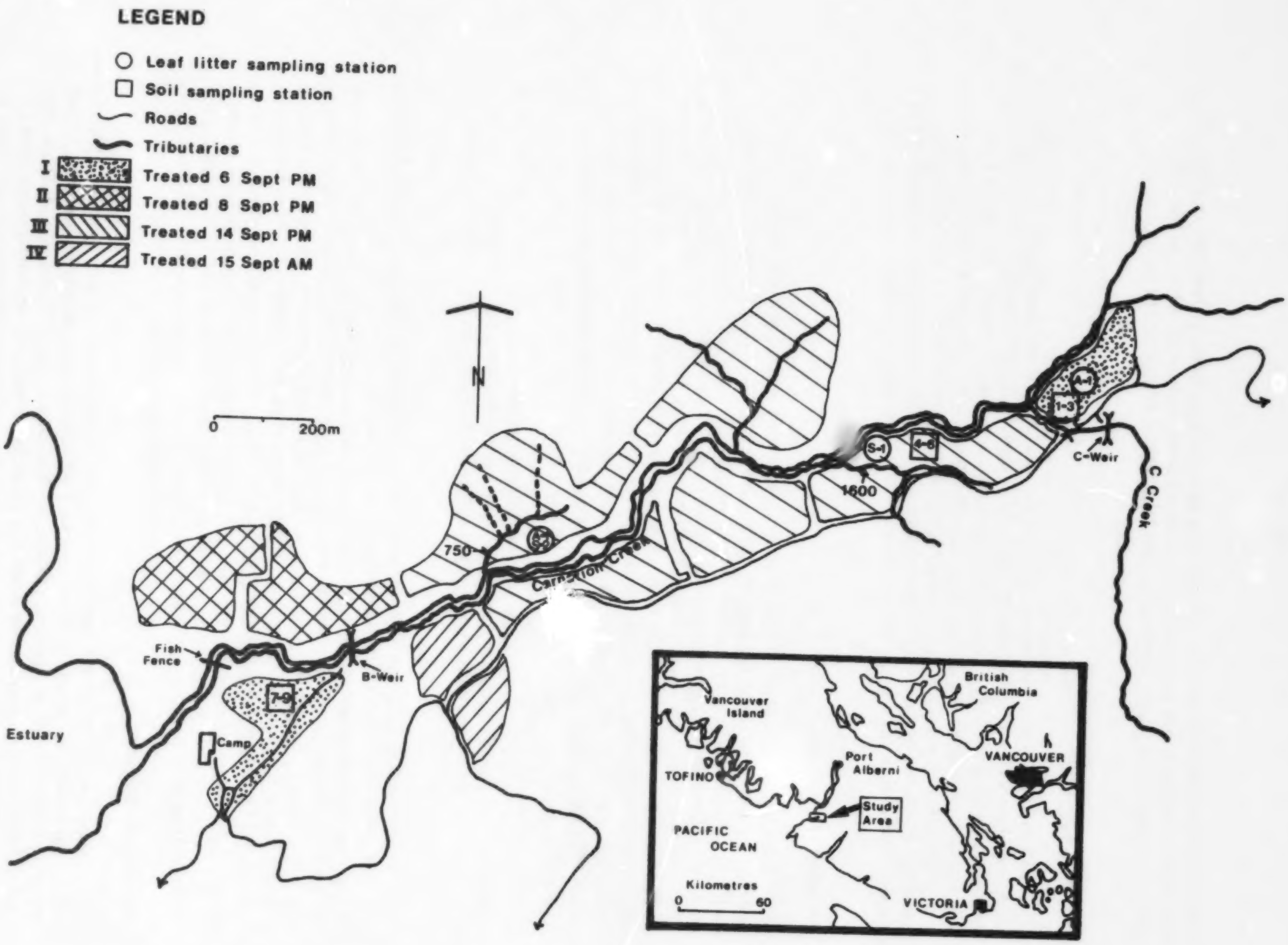

LEGEND
○ Leaf litter sampling station
☐ Soil sampling station
Roads
Tributaries
I Treated 6 Sept PM
II Treated 8 Sept PM
III Treated 14 Sept PM
IV Treated 15 Sept AM
N
0
200m
Estuary
Fish Fence
Camp
7-9
B-Weir
750
Carnation Creek
1600
S-1
4-6
A-1
1-3
C-Weir
C Creek
Vancouver Island
British Columbia
TOFINO
Port Alberni
Study Area
VANCOUVER
PACIFIC OCEAN
Kilometres
0
60
VICTORIA

Figure 1. Location of the Carnation Creek Study Area and Terrestrial Sampling Stations.

interception estimates were at sites removed from those used to determine leaf-litter residues. A total of 20 $m^2$ surface area of nylon mesh was placed under appropriate species to trap leaf-litter, thus providing a sample substrate for leaf-litter residue determinations.

## Herbicide Application

ROUNDUP (isopropylamine salt of glyphosate) was applied at a nominal rate of 2 kg/ha active ingredient with a Bell-47 helicopter and a MICROFOIL BOOM equipped with 1.5 mm hayrack nozzles (Reynolds et al. 1989). The volume application rate was calibrated to be 258.25 L/ha. Due to inclement weather conditions, chemical applications were made over a 9-day period on 11 spray blocks (Fig. 1 and Table 2). During application to the pertinent areas, meteorological conditions monitored by the weather station established near the mouth of Carnation Creek were as follows: relative humidity - 61%, air temperature - 24°C, windspeed - 11 km/h.

## Sampling Methodology

Soil samples were obtained from each sampling station with a Campbell soil coring device, as described elsewhere (Feng and Klassen 1986). Soil cores were taken to a depth of 30 cm and each core was sliced into three sections corresponding to soil depths of 0-5 cm, 5-15 cm and 15-30 cm layers respectively. Volume, fresh weight and air dry weight were determined for each layer. These determinations allowed computation of moisture content, bulk density and residue concentration on both an area and dry weight basis. Soil samples were collected before and immediately after chemical application and thereafter on an increased temporal spacing (i.e. 3 day intervals for the first month, weekly during the second month, biweekly for the third month and monthly between the fourth and twelfth months). The exact times of soil sampling are presented in Appendix 1.

Aluminum foil sheets (400 $cm^2$) on corrugated cardboard plates were used to provide initial deposit samples. Deposit sampling sheets were collected immediately following chemical application, packaged, stored and shipped according to procedures as described by Feng and Klassen (1986).

Fresh leaves were collected immediately following treatment by felling a representative tree (red alder) or clipping brush (salmonberry). Individual leaves were then harvested to provide a composite sample for each species at each sampling site. Leaf senescence began in mid-September 1984, and leaf-litter samples were collected from nylon mesh traps between 01 October and 30 November. Samples of leaf-litter were collected biweekly generally and on a weekly schedule during the peak leaf fall period. Details of sampling methodologies for all substrates are reported by Feng and Klassen (1986).

## Residue Analysis

### Formulation analysis

Samples of ROUNDUP formulation (356 g a.i./L) were collected before mixing for application and kept at ambient temperature. Quadruplicate 1 mL aliquots were serially diluted ($10^5$ X) with $KH_2PO_4$ buffer solution as described in Table 3. The diluents were filtered with Millipore filter units (Millex HV, 0.45 $\mu$m) and subjected to high performance liquid chromatographic (HPLC) analysis for glyphosate and its major degradation product - aminomethylphosphonic acid (AMPA).

Table 3. Specifications of HPLC instrumentation

| Component | Specification |
|---|---|
| HPLC System: | Varian Model 5560 Ternary HPLC, Model 8085 Autosampler |
| Detector: | UV-200 variable wavelength detector set at 570 nm |
| Derivatization System: | Ninhydrin post column reactor (100°C)<br>System V Model 5000 (Varian Inc.) |
| Analytical Column: | Bio-Rad Aminex A-9 10 cm X 4.6 mm i.d. |
| Guard Column: | Bio-Rad Aminex A-9 ($K^+$ form cartridge) |
| Mobile Phase: | 0.005 M $KH_2PO_4$ buffer in 4% methanol pH = 1.9 |
| Flow Rate: | 0.5 mL/min (iso-cratic) |
| Column Temperature: | 50°C |

## Tank mix analysis

Tank-mix samples (400 mL) collected immediately prior to application to Treatment Area III, were stored frozen until analyzed. Duplicate 1 mL aliquots were diluted ($10^3$ X) in buffer solution, filtered and analyzed for both glyphosate and AMPA, as described above.

## Deposit collector sample analysis

Residues of glyphosate and AMPA were extracted from the deposit collecting sheet by a multiple rinsing/shaking and sonicating procedure using 0.1 N HCl as the extraction solvent (Feng and Klassen 1986). The extracts were then subjected to cation and anion exchange column cleanup prior to quantification by HPLC analysis. Herbicide quantities (glyphosate plus AMPA as glyphosate equivalent) on the deposit plates, were converted to kg/ha rates using the equation: kg/ha = $2.5 \times 10^{-4} \times R$ where R = total residue (μg) per deposit collector (400 $cm^2$ ).

## Leaf-litter and foliage sample analysis

Whole samples of foliage and leaf-litter were air-dried and macerated by passage through a Hobart chopper. Finely chopped particles were mixed in large, inflated, plastic bags, to provide a homogeneous sample. From the homogenized samples, two subsamples (5 g) were taken and used for determination of oven-dry weight and for residue content, respectively. The analytical procedures used for leaf litter and foliage sample analyses are detailed in Thompson et al. (1989). Briefly, the method involves triplicate extraction with 0.5 M $NH_4OH$, pre-concentration on an anion exchange column, cleanup via cation exchange, evaporation, solvation in mobile phase solution and HPLC analysis (Table 3). Results were corrected for recovery efficiency of the analytical method (Table 4) and reported as μg per g of oven-dried leaf tissue.

Table 4. Validation data for analytical methods

| Substrate | Fortif. level | N | Analyte | % Recovery Mean ± s.d. (cv%) | LOD* | LOQ** |
|---|---|---|---|---|---|---|
| Deposit Collector | | | | | + | + |
| Humus Soils | 0.1-6.0 | 132 | GLYPH | 77.7 ± 8.9 (11.56) | 0.05 | 0.10 |
| | .025-1.5 | 132 | AMPA | 67.7 ± 10.9 (16.09) | 0.01 | 0.03 |
| Mineral Soils | 0.1-6.0 | 30 | GLYPH | 73.5 ± 7.7 (10.53) | 0.02 | 0.05 |
| | .025-1.5 | 30 | AMPA | 58.2 ± 10.9 (12.77) | 0.02 | 0.05 |
| Leaf Litter (s) | 0.5-5.0 | 4 | GLYPH | 84.4 ± 5.3 (6.25) | 0.10 | 0.30 |
| | 0.1-1.0 | 4 | AMPA | 54.7 ± 1.7 (3.21) | 0.03 | 0.08 |
| Leaf Litter (a) | 0.5-5.0 | 4 | GLYPH | 81.3 ± 7.7 (9.47) | 0.10 | 0.30 |
| | 0.1-1.0 | 4 | AMPA | 60.9 ± 12.2 (20.03) | 0.03 | 0.08 |

All values presented in terms of ppm = µg/g dry mass (for solids).

* LOD = limits of detection = detector response equivalent to 2X S:N ratio.

**LOQ = limits of quantification = detector response 6X S:N ratio.

+LOD and LOQ values for deposit collectors equate to 2.5 X 10-5 and 1.25 X $10^{-4}$ kg/ha respectively.

Soil sample analysis

Soil samples obtained from the Carnation Creek study site were immediately frozen, shipped and stored under cold (-10°C), dark conditions until analysis. Owing to the large number of samples of various substrates taken during the course of the study and the requirement for priority on aquatic substrates, soil samples were not analyzed until 2 years after the study was initiated.

Subsamples (5 g) of air-dried and homogenized soils were extracted three times with 0.5 M $NH_4OH$. Extracts were diluted to 1800 mL, concentrated on an anion exchange column and processed as described above for leaf-litter and foliage samples. Aliquots (100 µL) of the final solutions were analyzed by HPLC (Table 3). Results were corrected for recovery efficiency of the analytical method (Table 4) and reported as µg of glyphosate per g of air-dried soil. For samples taken at 0-time, soil residues (glyphosate + AMPA as glyphosate equivalent) were converted from total micrograms found to initial deposit in terms of kg/ha, using the following equation:

$$R/A/10 = kg/ha$$

where R = initial residue (total µg of glyphosate and AMPA)

A = cross-sectional surface area of soil auger (78.54)

### High Performance Liquid Chromatography (HPLC)

Determination of glyphosate residues in environmental substrates continues to be one of the more difficult aspects of herbicide analytical chemistry. A variety of methods are described in the literature, with some validation data also available (Lundgren 1986; Monsanto 1986; Seiber et al. 1984; Glass 1983; Edwards et al. 1980; Moye and St. John 1980; Monsanto 1977). The analytical methods used for determination of AMPA and glyphosate in soil and leaf litter samples were modifications of the Monsanto (1986, personal communication) method, supplied courtesy of Dr. J. Cowell, Monsanto Co. Inc., St. Louis, Missouri. A detailed description of the method is given in Thompson et al. (1989). Briefly, the method employs cation exchange - HPLC, coupled with a post-column ninhydrin derivatization to separate glyphosate and AMPA analytes from co-extractive interferences and provide derivatization products capable of absorbing in the visible portion of the spectrum. Characteristics of the HPLC system are described in Table 3.

Preliminary validation tests of the analytical method indicated that the determination of glyphosate and AMPA in fortified substrates derived from the Carnation Creek study site were relatively accurate and precise, with no co-extractive interferences at the retention times of the two analytes. Throughout the course of analytical determinations a quality control (QC) program was conducted. Results of the QC samples, which were processed and analyzed daily in conjunction with field samples, confirmed that the accuracy and precision of the method (Table 4). While not ideal, these data were similar to reported values in the available literature. The QC data were subsequently used to correct the field sample data for recovery efficiency of the analytical method.

## RESULTS AND DISCUSSION

### Formulation Analysis

Analysis of the ROUNDUP formulation utilized for the herbicide application in this study indicated that the amount of active ingredient (glyphosate) was 363 g/L ± 2% cv, approximately 2% in excess of the label concentration (356 g/L). No AMPA was detected in the formulation, which had been stored at ambient temperature for 3 months.

### Tank Mix Analysis

Results of the analyses conducted on the tank mix showed concentrations of 7889 and 58 $\mu$/L of glyphosate and AMPA respectively. There was a 6% v/v contamination of the tank-mix from a six-day old mixture used to spray adjacent areas of the watershed. The amount of AMPA detected (0.7% of glyphosate concentration in the tank mix) indicated a 13% degradation of glyphosate in the previous mixture after six days of storage at ambient temperature. The initial concentration of the tank mix was corrected by converting the AMPA concentration to a glyphosate equivalence. The corrected value was 103% of the concentration required to yield an application rate of 2 kg a.i/ha.

### Deposit Collector Analysis

Analysis of deposit collectors placed around the periphery of the sampling stations allowed empirical estimation of the initial deposit rate and subsequent comparison with similar estimates based on soil residues. Thus variability of initial chemical deposition both within and among site locations could be determined. The results indicate that the deposit collectors consistently estimated higher deposition rates with greater precision than estimates from soil residues. Differences in rate estimates derived from deposit collectors and soil residues were significant (P >0.05) for the upper and middle sampling locations. This discrepancy may be due in part to differences in replication (n= 3 for soil samples per location; n=8 for deposit collector samples per location) and to interception of chemical by ground vegetation. Analysis of variance (ANOVA) and multiple comparison procedures (LSD and Bonferroni), indicated that mean rate estimates as determined by deposit collectors, were significantly different for each of the three locations (P >0.05). Mean rate estimates at the three different sites as derived from soil residues were not significantly different due to greater variation in these samples.

The average empirical rate estimates of 2.52 and 1.85 kg/ha, as determined by deposit collector analysis and by soil residue analysis respectively, were reasonably close to the nominal value of 2.0 kg/ha (Table 5). However, significant differences between deposition rates at various sites, as previously noted, indicate extreme variability in chemical deposition to different areas of the watershed (section on Herbicide Application and Table 5). Both methods of empirical estimation indicated that application rates for the lower portion of the watershed were higher than for the upper watershed. The mid-watershed site (Treatment Area III) received the least chemical deposition, probably owing to the gusty wind conditions prevailing during the mid-afternoon application (Table 2). The high mean value in soil residues recorded for the lower sampling location, resulted from one station (station 8) with a reported initial deposit equivalent to 5.67 kg/ha. No explanation could be found for this anomalous result. Initial levels of AMPA were less than 2% of corresponding glyphosate residues for all deposit collector samples, but varied between 4 and 13% for initial deposit as determined from soil sample residues. The higher levels of AMPA in O-time soil samples, when compared with deposit collector samples, may be indicative of minor degradation of glyphosate during the 2-year storage period for soil samples.

Table 5. Comparison of nominal and empirical estimates of initial glyphosate deposition at Carnation Creek Watershed study sites

| Sampling location | Treat. area | Initial deposition rate estimates (kg/ha)<br>* | <br>Deposit collector** | <br>Soil residue** |
|---|---|---|---|---|
| Stations 1-3 (Upper Watershed) | I | 2.0 | 2.54 ± 0.32 (13% cv)A | 1.72 ± 0.31 (18% cv) |
| Stations 4-6 (Mid Watershed) | III | 2.1 | 1.62 ± 0.24 (15% cv)B | 0.60 ± 0.09 (16% cv) |
| Stations 7-9 (Lower Watershed) | I | 2.0 | 3.42 ± 0.46 (14% cv)C | 3.23 ± 2.30 (71% cv) |
| Overall Average | | 2.0 | 2.52 ± 0.90 (36% cv) | 1.85 ± 1.32 (71% cv) |

* Nominal rates as reported by Reynolds *et al*. (1989).

** Values based on total residue (glyphosate plus AMPA) with n=8 for deposit collectors and n=3 for soil residues.

Deposit collector values followed by different letters are significantly different (P >0.05) as determined by LSD and Bonferroni multiple comparison procedures.

Within each sampling location (i.e. amongst replicates), the variability (as denoted by the coefficient of variation) was similar for deposit collectors and soil residue estimates, with the exception of the lower location. The higher variation at this location is also the result of one anomalous data point as described previously.

Results of the quality control program, comprising over 160 samples analyzed in conjunction with field samples throughout the 8-month analysis period, indicated that analytical variability (coefficient of variation) for soil residue determinations was less than 12% for glyphosate and less than 16% for AMPA. These results indicate that significant differences exist in deposition between various locations, however, the average deposition for the entire watershed is reasonably close to the nominal rate. The differences observed may be attributed to variable meteorological and application parameters for different spray blocks. The data also indicate that greater replication in soil residue sampling would be required to achieve precision equivalent to the deposit collector method for estimating initial deposit.

## Leaf-Litter and Foliage Sample Analysis

Results of the leaf litter and foliage sample analyses are presented in Table 6. In general, the data show that residues decline over time in both salmonberry and alder leaf litter. Statistical analysis (ANOVA) of the results indicated that the decline in glyphosate residues is significant for both alder and salmonberry (P >0.0589 and P >0.0001 respectively). This rapid dissipation from foliage may be attributed to wash-off caused by the rainfall event (39 mm) that occurred 23 h post-application. Residues continued to decline throughout the observation period to the extent that less than 0.1% of initial levels remained 75 days post-application.

Table 6. Residues of glyphosate and AMPA associated with leaf litter of two target species from the Carnation Creek*

| Days (post-spray) | Alder | | Salmonberry | |
|---|---|---|---|---|
| | Glyphosate | AMPA | Glyphosate | AMPA |
| 0 | 261.0 ± 153.0 | 2.9 ± 2.5 | 447.6 ± 117.7 | 6.2 ± 0.1 |
| 15 | 12.5 ± 9.8 | 0.3 ± 0.1 | 19.2 ± 10.6 | 1.2 ± 0.0 |
| 29 | 1.2 ± 1.2 | 0.1 ± 0.1 | 1.9 ± 0.9 | 0.1 ± 0.0 |
| 45 | 0.5 ± 0.3 | 0.1 ± 0.0 | 0.9 ± 0.4 | 0.1 ± 0.0 |
| 58 | 0.2 ± 0.0 | 0.0 ± 0.0 | 0.3 ± 0.1 | 0.1 ± 0.0 |
| 75 | 0.2 ± | 0.1 | 0.3 ± 0.1 | 0.1 ± 0.0 |

*Residue values are means of two replications in µg per gram dry tissue.

Residues of AMPA found on either type of foliage immediately after application were less than 2% of glyphosate residues, a result that is in good agreement with both the tank mix analysis and deposit collector results. No transient increase in AMPA residue was observed for either foliage type after leaf fall.

The results of leaf tissue analyses indicate that both target species intercepted a relatively large amount of chemical and that leaf-litter contained much less residue, which dissipated slowly with time. In general, these results support those of Lund-Hoie (1979), who found that only 20% of the glyphosate initially applied was absorbed in ash and birch foliage and that 35% of the absorbed amount was decomposed within 2 months, little being recovered as AMPA.

The data derived from this experiment suggest that glyphosate residue levels in leaf-litter of major brush species would present an insignificant, transient source of chemical input onto forest floor or into streams. One may hypothesize that foliage residues present a major source for ecosystem contamination only through wash-off of unabsorbed chemical, with contamination via leaf-fall being relatively minor. Further research is required on the aspect of binding and subsequent wash-off of glyphosate from treated leaf surfaces.

### Soil Sample Analysis

Leaching potential

Residue analyses were conducted on each of three individual layers - 0-5 cm (organic), 5-15 cm (organic), 15-30 cm (organic and mineral) - from each soil core. In addition, at sampling dates beyond 150 days post-application, a fourth layer [30-35 cm (mineral)] was obtained and analyzed. Results of these analyses are presented in terms of means for replicate samples taken throughout the observation period at each of the soil sampling locations (upper, middle and lower watershed). The histograms and tabular data indicate the percent of total residue distributed throughout the various layers (Fig. 3 & Appendices). Quantifiable residues of glyphosate were found in only one of the 30-35 cm layer samples, the residue (0.46 ppm) being equivalent to 11.5% of the total found in the core. This anomalous result was attributed to mislabeling during the air-drying process, however, positive proof of this could not be obtained from available laboratory records. In general terms, virtually all ( >90%) of the residue was associated with the 0-5 cm organic layer. Two anomalous values were observed at day 60 for glyphosate in the lower watershed site (30.28% of total glyphosate in layer C) and at day 360 for AMPA in the lower watershed (27.28% of total AMPA in layer C). Although of little practical importance, higher mean residue levels in layer C from stations 7-9 relative to other sites indicated a slightly greater tendency towards leaching in these soils. No differences in leaching potential between the seasonally flooded and well-drained soil sites was apparent.

Results of the vertical distribution determinations indicate that neither glyphosate nor AMPA are susceptible to leaching. The findings are consistent with the general literature (Helling 1971; Sprankle *et al*. 1975; Rueppel *et al*. 1977; Damanakis 1976; and Edwards *et al*. 1980) and support the conclusion of Torstensson (1985), who stated that glyphosate is practically immobile in soil.

The majority of research conducted on the adsorption of glyphosate to soils or soil fractions (i.e. mineral components), suggests that glyphosate is bound to soils through the phosphonic acid moiety and that sorption is positively correlated with clay content, cation exchange capacity and unoccupied phosphate sorption capacity (Sprankle *et al*. 1975; Hance 1976; Glass 1987). Since Carnation Creek soils are characterized by a relatively high cation-exchange capacity and organic matter content, especially in the upper 15 cm layers (Table 1), we suggest that the lack of vertical mobility exhibited by glyphosate in these soils is due to strong adsorption to cation saturated clays and/or organic matter in the upper soil horizons. An essentially identical leaching pattern was exhibited by AMPA in this study.

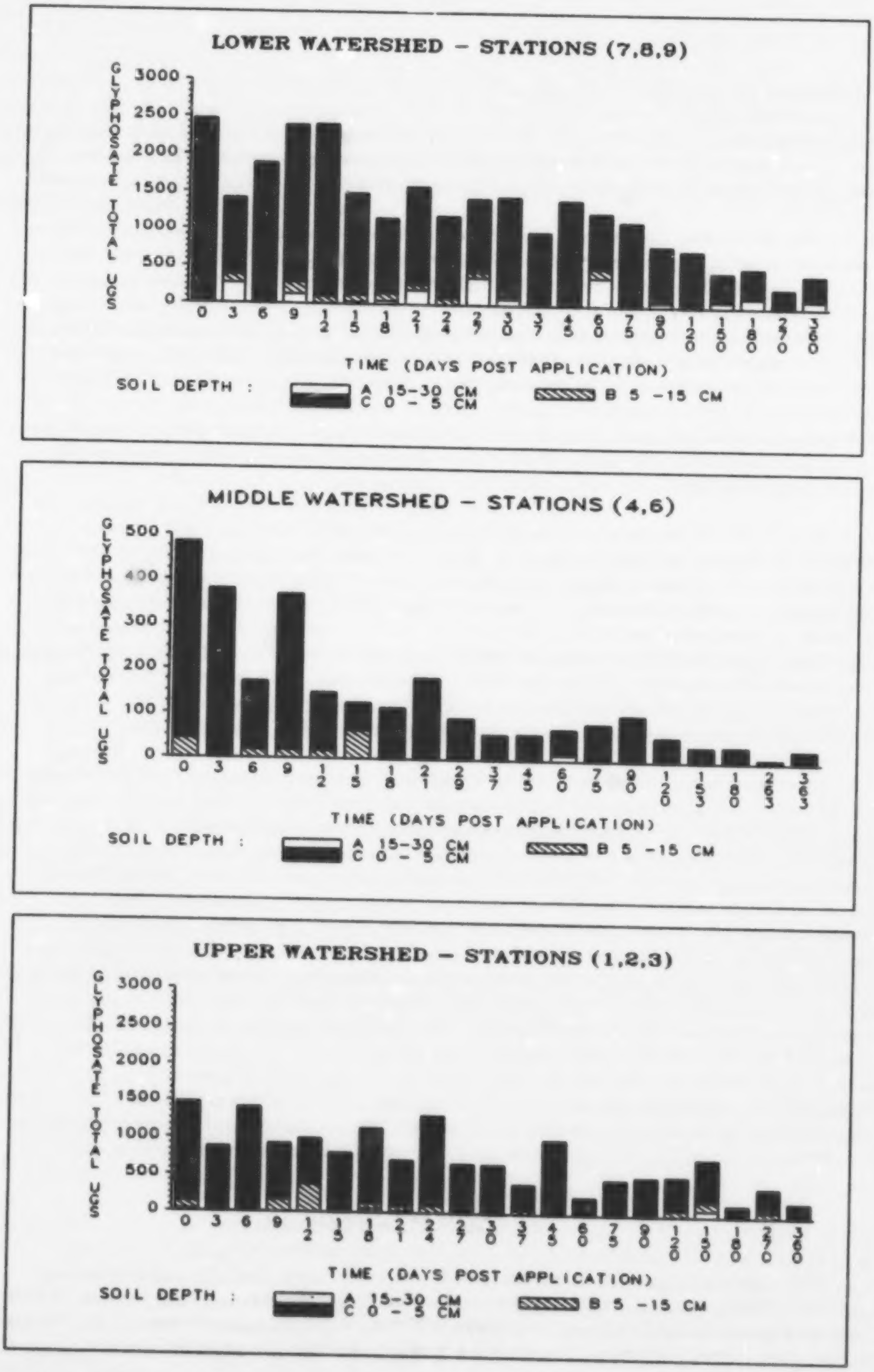


Figure 2. Persistence and distribution of glyphosate and AMPA in Carnation Creek Watershed Study soils.

**Persistence**

Computation of mean soil residues of glyphosate and AMPA in the 0-30 cm soil layer was done at each sampling time to allow determination of persistence in each sampling location - upper, middle and lower watershed. (Figure 2 and Appendices).

Although the data clearly show that residues decline over time (Fig. 2), variability within replicates resulted in poor regression coefficients for both linear and log transformed data $(.17 < r \quad > .46)$, which prohibited the use of regression equations for estimation of time to 50% and 90% dissipation ($DT_{50}$ and $DT_{90}$, respectively). In addition, no statistically valid comparisons could be made with respect to persistence of glyphosate or AMPA in seasonally flooded soils or in well-drained soils. Quantifiable residues of both glyphosate and AMPA did remain after 360 days. In terms of percent of initial residues, these values ranged from 6-18% and 16-27% for glyphosate and AMPA, respectively. AMPA residues, which were initially very low (4-13% of glyphosate residues), followed a pattern of transient increase and subsequent decline at all sampling locations (Appendices 2.1-2.3). Peak residue means were less than 40% of mean initial glyphosate residues for the respective sites.

The general decline in glyphosate residues over time at all three sampling locations, coupled with transient increase in AMPA residues is indicative of microbial degradation of glyphosate in the soils studied. Although accurate estimates of $DT_{50}$ and $DT_{90}$ could not be made from regression analysis, averaging glyphosate residues for all sample locations indicated that glyphosate residues were consistently less than 50% of initial residues after 45-60 days post-application. At the end of the observation period, both glyphosate and AMPA residues were lowest in the middle watershed site. Due to the nature of this site (low-lying and seasonally flooded), it is probable that reduced residue levels could be attributed to movement of chemical away from the sampling with surface water present at time of application.

Laboratory experiments conducted by Torstensson and Stark (1981), showed that the time to 50% degradation of glyphosate in a number of different forest soils was quite variable, ranging from 6 days in an iron podsol to 200 days in a podsol with ashes. Torstensson (1985) noted that the variable rate of degradation of glyphosate cannot be correlated to a single soil factor, but reflects the general microbial activity of the soils being investigated, which in turn is affected by a mutiplicity of environmental factors. Since the influencing factors may vary from soil to soil and/or from year to year, prediction or comparison of glyphosate persistence, based on either laboratory studies or field studies, should be avoided unless most of the important influencing variables are quantified or controlled. Newton et al. (1984) estimated time to 50% dissipation of glyphosate as 40.2 days based on the results of a study conducted in a semi-arid Oregon forest watershed. However, owing to the differences between the two studies, especially with respect to the method by which the persistence estimates were derived, no valid conclusion can be drawn regarding glyphosate persistence estimates (similarity or lack thereof). In general terms, however, the results of Oregon study and the Carnation Creek study are in agreement. In short, the Carnation Creek study provides no evidence of extraordinary soil persistence of either glyphosate or AMPA.

## ACKNOWLEDGEMENTS

This research, supported under the British Columbia Forest Resource and Development Agreement (FRDA), was conducted by members of the Forest Pest Management Institute (FPMI), of the Canadian Forestry Service. Cooperation of the British Columbia Ministry of Forests, the Pacific Forestry Centre (PFC), Fisheries and Oceans Canada, MacMillan Bloedel Ltd., and Monsanto Canada

Inc. were integral to the success of this project. Herbicide application was contracted to Rotor Vegetation Control (R. Rowe) and Alpine Helicopters (D. Gubbels and D. Cholka) both of Calgary Alberta, was coordinated by Dr. P. Reynolds (FPMI). The authors sincerely appreciate and acknowledge the excellent technical assistance in residue analysis of B. Staznik, T. Buscarini, V. Manniste-Squire, and L. MacDonald (FPMI), and of H. Klassen and D. DeKoven (V.A. Poulin and Assoc. Ltd.) who performed the field sampling.

## REFERENCES

Cowell, J.E., J.L. Kunstman, P.J. Nord, J.R. Steinmetz and G.R. Wilson. 1986. Validation of an analytical residue method for analysis of glyphosate and metabolite: An interlaboratory study. J. Agric. Food Chem. 34:955-960.

Damanakis, M.E. 1976. Behaviour of glyphosate in the soil (adsorption. leaching. degradation). Annales del l'Institut Phytopathologique Benaki. 11:153-167. (As cited by Torstensson. L. 1985. Behaviour of glyphosate in soils. pp. 137-150 In: The Herbicide Glyphosate. E. Grossbard and D. Atkinson (eds.). Butterworths. London.

Dryburg, J.G. 1982. Carnation Creek logging and silvicultural treatment program. pp. 36-43 In G.F. Hartman (ed.) Proceedings of the Carnation Creek workshop. a 10-year review. February 24-26, 1982. Malaspina College. Nanaimo. B.C.

Edwards, W.M., G.B. Triplett and R.M. Kramer. 1980. A watershed study of glyphosate transport in runoff. J. Environ. Qual. 9(4): 661-665.

Feng, J.C. and H.D. Klassen. 1986. Forestry field and laboratory manual for herbicide residue sampling, sample processing and reporting. Can. For. Serv., For. Pest Manage. Inst., Sault Ste. Marie, Ont. Inf. Rep. FPM-X-72. 38 p.

Glass, R.L. 1983. Liquid chromatographic determination of glyphosate in fortified soil and water samples. Journal Agric. Food Chem. 31:280-282.

Glass. R.L. 1987. Adsorption of glyphosate by soils and clay minerals. Abstracts of The American Chemical Society National Meeting. September 7-10. 1986. Anaheim. California.

Hance, R.J. 1976. Adsorption of glyphosate by soils. Pesticide Science. 7:363-366.

Helling, C.S. 1971. Pesticide mobility in soils. 1. Parameters of soil thin-layer chromatography. Proceedings of the Soil Science Society of America. 35: 732-737.

Hetherington, E.D. 1982. A first look at logging effects on the hydrologic regime of Carnation Creek experimental watershed. pp. 11-15 In G.F. Hartman (ed.) Proceedings of the Carnation Creek workshop. a 10-year review. February 24-26. 1982. Malaspina College. Nanaimo, B.C.

Krajina, V.J. 1969. Ecology of forest trees in British Columbia. pp. 1-146 In V. Krajina and R. Brooks (eds.) Ecology of western North America. Vol. 2. Nos. 1 and 2. Dep. Botany. Univ. B.C., Vancouver, B.C.

Lundgren, L.N. 1986. A new method for the determination of glyphosate and (aminomethyl) phosphonic acid residues in soils. J. Agric. Food Chem. 34:535-538.

Lund-Hoie, K. 1976. The correlation between the tolerance of Norway spruce (*Picea abies*) to glyphosate (N-phosphonomethylglycine) and the uptake, distribution and metabolism of the herbicide in spruce plants. As cited in: D. Coupland. 1985. Metabolism of glyphosate in plants. Chapter 3 p. 25-34. In E. Grossbard and D. Atkinson (eds). The Herbicide Glyphosate Butterworths, London.

Lund-Hoie, K. 1979. The physiological fate of glyphosate-$^{14}$C in *Betula verrucosa* and *Fraxinus excelsior*. The effect of ammonium sulphate and the environment on the herbicide. As cited in: D. Coupland. 1985. Metabolism of glyphosate in plants. Chapter 3 p. 25-34. In E. Grossbard and D. Atkinson (eds) The Herbicide Glyphosate. Butterworths, London.

Monsanto. 1977. Methods for individual pesticide residues "Glyphosate" In: Pesticide Analytical Manual 1977. Vol. 2. Food and Drug Administration. Washington. D.C. Pest. Reg. Sec. 180:364.

Moshier, L.J. and D. Penner. 1976. Factors influencing microbial degradation of $^{14}$C-Glyphosate to $^{14}$C-CO$_2$, in soil. Weed Science 26:686-691.

Moye, H.A. and P.A. St. John. 1980. A critical comparison of pre-column and post-column fluorogenic labeling for the HPLC analysis of Pesticide Residues. In Harvey J. Zweig Jr. (ed.) Pesticide Analytical Methodology. ACS Symposium Series 136:89-102. American Chemical Society. Washington, D.C.

Muller, P.M., C. Rosenberg. H. Siltanen and T. Wartiovaara. 1981. Fate of glyphosate and its influence on nitrogen-cycling in two Finnish agricultural soils. Bulletin of Environmental Contamination and Toxicology. 27:724-730.

Newton, M., K.M. Howard, B.R. Kelpsas, R. Danhaus, P.M. Lottman and S. Dubelman. 1984. Fate of glyphosate in an Oregon forest ecosystem. J. Agric. Food Chem. 32: 1144-1151.

Putnam, A. 1976. Fate of glyphosate in deciduous fruit trees. Weed Science. 24:425-430.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. An overview of Carnation Creek herbicide study: historical perspective, experimental protocols, and spray operations. This proceedings.

Rueppel, M.L., B.B. Brightwell, J. Schaefer and J.T. Marvel. 1977. Metabolism and degradation of glyphosate in soil and water. J. Agric. Food Chem. 25:517-528.

Seiber, J.N., M.M. McLesney, R. Kon and R.A. Leavitt. 1984. Analysis of glyphosate residues in kiwi fruit and asparagus using high performance liquid chromatography of derivatized glyphosate as a cleanup step. J. Agric. Food Chem. 32:678-681.

Sprankel, P., W.F. Meggitt and D. Penner. 1975. Adsorption, mobility and microbial degradation of glyphosate in the soil. Weed Science. 23:229-234.

Thompson, D.G., B. J.E. Cowell, R.J. Daniels, B. Staznik and L. MacDonald. 1989. An alternative method for quantification of glyphosate and AMPA Residues in organic and mineral soils, streams sediments and hard wood foliage. J. Assoc. Off. Anal. Chem. (in press).

Torstensson, L. 1985. Behaviour of glyphosate in soils. pp. 137-150 In E. Grossbard and D. Atkinson (eds.) The Herbicide Glyphosate. Butterworths, London.

Torstensson, L. and J. Stark. 1981. Decomposition of $^{14}$C-labeled glyphosate in Swedish forest soils. pp. 72-79 In Proceedings of the EWRS Symposium on Theory and Practice of the Use of Soil Applied Herbicides.

APPENDIX 1.1 CARNATION CREEK SOIL RESIDUE DATA - GLYPHOSATE
SAMPLING LOCATION - LOWER WATERSHED (STATIONS 7,8,9)

| Time (days) | Total residue (µgs) (0-30 cm core) | Distribution of residues (%) | | |
|---|---|---|---|---|
| | | 0-5 cm | 5-15 cm | 15-30 cm |
| 0 | 2469.11 ± 1763.37 (71.4) | 98.33 | 1.67 | 0.00 |
| 3 | 1413.61 ± 749.08 (52.9) | 72.30 | 8.46 | 19.23 |
| 6 | 1889.74 ± 1061.57 (56.1) | 99.63 | 0.37 | 0.00 |
| 9 | 2391.87 ± 760.40 (31.7) | 86.64 | 7.85 | 5.51 |
| 12 | 2408.22 ± 1488.79 (61.8) | 95.82 | 4.18 | 0.00 |
| 15 | 1491.85 ± 838.63 (56.2) | 90.62 | 6.92 | 2.46 |
| 18 | 1156.54 ± 575.29 (49.7) | 85.69 | 9.78 | 4.53 |
| 21 | 1586.90 ± 196.94 (12.4) | 81.68 | 5.87 | 12.45 |
| 24 | 1197.29 ± 840.91 (70.2) | 92.21 | 7.79 | 0.00 |
| 27 | 1430.13 ± 552.84 (38.6) | 68.26 | 6.23 | 25.51 |
| 30 | 1456.88 ± 574.10 (39.4) | 89.28 | 3.98 | 6.73 |
| 37 | 989.57 ± 376.70 (38.0) | 99.33 | 0.67 | 0.00 |
| 45 | 1414.60 ± 2096.59 (148.2) | 100.00 | 0.00 | 0.00 |
| 60 | 1248.91 ± 1478.50 (118.3) | 59.14 | 10.58 | 30.28 |
| 75 | 1129.65 ± 687.63 (60.8) | 98.9 | 1.03 | 0.00 |
| 90 | 814.29 ± 532.17 (65.3) | 86.12 | 6.41 | 7.46 |
| 120 | 752.69 ± 518.08 (68.8) | 97.64 | 2.36 | 0.00 |
| 150 | 467.88 ± 425.77 (91.0) | 79.55 | 3.33 | 17.13 |
| 180 | 525.04 ± 244.47 (46.5) | 69.16 | 5.27 | 25.57 |
| 270 | 260.19 ± 154.83 (59.5) | 74.15 | 10.58 | 15.27 |
| 360 | 436.75 ± 177.72 (40.6) | 68.32 | 6.14 | 25.54 |

APPENDIX 1.2 CARNATION CREEK SOIL RESIDUE DATA - GLYPHOSATE
SAMPLING LOCATION - MIDDLE WATERSHED (STATIONS 4,6)

| Time (days) | Total residue (μgs) (0-30 cm core) | Distribution of residues (%) 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|---|---|
| 0 | 484.00 ----- | 91.05 | 9.95 | 0.00 |
| 3 | 379.76 ----- | 100.00 | 0.00 | 0.00 |
| 6 | 172.18 ± 217.39 (126.2) | 88.97 | 11.03 | 0.00 |
| 9 | 369.65 ± 370.68 (100.2) | 94.65 | 5.35 | 0.00 |
| 12 | 147.01 ± 96.94 (65.9) | 87.61 | 12.39 | 0.00 |
| 15 | 125.97 ± 2.45 (1.9) | 50.00 | 50.00 | 0.00 |
| 18 | 113.93 ± 73.58 (64.5) | 100.00 | 0.00 | 0.00 |
| 21 | 182.32 ± 126.05 (69.1) | 100.00 | 0.00 | 0.00 |
| 30 | 92.40 ± 60.28 (65.2) | 100.00 | 0.00 | 0.00 |
| 37 | 56.79 ± 6.57 (11.5) | 100.00 | 0.00 | 0.00 |
| 45 | 57.82 ± 32.02 (55.3) | 100.00 | 0.00 | 0.00 |
| 60 | 70.25 ± 4.94 (7.0) | 85.50 | 0.00 | 20.50 |
| 75 | 82.71 ± 44.68 (54.0) | 100.00 | 0.00 | 0.00 |
| 90 | 102.21 ± 36.71 (35.9) | 100.00 | 0.00 | 0.00 |
| 120 | 54.70 ± 59.69 (109.1) | 100.00 | 0.00 | 0.00 |
| 150 | 34.08 ± 14.40 (42.2) | 100.00 | 0.00 | 0.00 |
| 180 | 35.10 ± 2.84 (8.1) | 100.00 | 0.00 | 0.00 |
| 270 | 8.29 ± 11.73 (141.4) | 100.00 | 0.00 | 0.00 |
| 360 | 28.98 ± 4.22 (14.5) | 100.00 | 0.00 | 0.00 |

APPENDIX 1.3 CARNATION CREEK SOIL RESIDUE DATA - GLYPHOSATE
SAMPLING LOCATION - UPPER WATERSHED (STATIONS 1,2,3)

| Time (days) | Total residue ($\mu$gs) (0-30 cm core) | Distribution of residues (%) 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|---|---|
| 0 | 1476.96 ± 376.25 (25.5) | 89.02 | 7.97 | 2.01 |
| 3 | 878.16 ± 567.78 (64.6) | 96.09 | 3.91 | 0.00 |
| 6 | 1410.93 ± 1238.64 (87.7) | 96.21 | 3.79 | 0.00 |
| 9 | 926.39 ± 983.53 (106.1) | 81.82 | 18.18 | 0.00 |
| 12 | 992.08 ± 1552.66 (156.5) | 61.17 | 38.83 | 0.00 |
| 15 | 809.63 ± 882.92 (109.0) | 96.00 | 4.00 | 0.00 |
| 18 | 1140.02 ± 1048.37 (91.9) | 89.79 | 6.06 | 4.16 |
| 21 | 709.89 ± 472.23 (66.5) | 86.37 | 9.65 | 3.99 |
| 24 | 1313.89 ± 1048.25 (79.7) | 91.15 | 8.85 | 0.00 |
| 27 | 669.76 ± 560.39 (83.6) | 93.94 | 6.06 | 0.00 |
| 30 | 668.25 ± 226.16 (33.8) | 97.44 | 0.00 | 2.56 |
| 37 | 408.28 ± 282.19 (69.1) | 84.08 | 15.92 | 0.00 |
| 45 | 1004.85 ± 1182.40 (117.6) | 99.58 | 0.42 | 0.00 |
| 60 | 238.99 ± 174.70 (73.1) | 100.00 | 0.00 | 0.00 |
| 75 | 483.30 ± 44.22 (9.1) | 95.89 | 4.11 | 0.00 |
| 90 | 522.29 ± 130.66 (25.0) | 97.68 | 2.32 | 0.00 |
| 120 | 533.29 ± 486.51 (91.2) | 83.45 | 16.55 | 0.00 |
| 150 | 782.87 ± 523.55 (66.8) | 73.40 | 15.56 | 11.04 |
| 180 | 157.71 ± 82.23 (52.1) | 87.29 | 12.71 | 0.00 |
| 270 | 394.36 ± 332.45 (84.3) | 80.95 | 19.05 | 0.00 |
| 360 | 198.07 ± 116.21 (58.6) | 100.00 | 0.00 | 0.00 |

APPENDIX 2.1 CARNATION CREEK SOIL RESIDUE DATA - AMPA
SAMPLING LOCATION - LOWER WATERSHED (STATIONS 7,8,9)

| Time (days) | Total residue ($\mu$gs) | Distribution of residues (%) | | |
|---|---|---|---|---|
| | (0-30 cm core) | 0-5 cm | 5-15 cm | 15-30 cm |
| 0 | 101.24 ± 68.52 (67.68) | 100.00 | 0.00 | 0.00 |
| 3 | 181.44 ± 78.25 (43.13) | 95.28 | 2.51 | 2.20 |
| 6 | 163.56 ± 70.24 (42.95) | 100.00 | 0.00 | 0.00 |
| 9 | 238.59 ± 20.68 ( 8.67) | 92.72 | 7.28 | 0.00 |
| 12 | 342.58 ± 213.01 (62.18) | 92.76 | 7.24 | 0.00 |
| 15 | 274.70 ± 130.11 (47.36) | 96.02 | 3.98 | 0.00 |
| 18 | 334.51 ± 197.41 (59.02) | 84.75 | 12.48 | 2.78 |
| 21 | 299.13 ± 119.41 (39.92) | 81.99 | 8.59 | 9.42 |
| 24 | 391.22 ± 66.67 (17.04) | 91.87 | 6.36 | 1.78 |
| 27 | 588.42 ± 47.93 ( 8.15) | 78.94 | 10.10 | 10.96 |
| 28 | 561.67 ± 0.00 ( 0.00) | 69.15 | 14.43 | 16.43 |
| 30 | 350.53 ± 56.84 (16.22) | 94.07 | 5.93 | 0.00 |
| 37 | 186.30 ± 56.53 (30.34) | 100.00 | 0.00 | 0.00 |
| 45 | 369.53 ± 201.56 (54.55) | 100.00 | 0.00 | 0.00 |
| 60 | 389.49 ± 199.36 (51.19) | 90.30 | 9.70 | 0.00 |
| 75 | 474.77 ± 370.03 (77.94) | 100.00 | 0.00 | 0.00 |
| 90 | 530.51 ± 183.35 (34.56) | 87.94 | 6.13 | 5.92 |
| 120 | 281.64 ± 154.54 (54.87) | 96.77 | 3.23 | 0.00 |
| 150 | 342.28 ± 106.88 (31.23) | 87.06 | 7.22 | 5.73 |
| 180 | 470.50 ± 308.24 (65.51) | 73.66 | 15.45 | 10.89 |
| 270 | 614.96 ± 304.59 (49.53) | 81.02 | 12.16 | 6.82 |
| 360 | 583.37 ± 372.03 (63.77) | 66.99 | 5.83 | 27.18 |

APPENDIX 2.2 CARNATION CREEK SOIL RESIDUE DATA - AMPA

SAMPLING LOCATION - MIDDLE WATERSHED (STATIONS 4,6)

| TIME (DAYS) | TOTAL RESIDUE (UGS) (0 - 30 CM CORE) | DISTRIBUTION OF RESIDUES (%) | | |
|---|---|---|---|---|
| | | 0-5 CM | 5-15 CM | 15-30 CM |
| 0 | 62.13 ± 37.56 (60.46) | 100.00 | 0.00 | 0.00 |
| 6 | 77.13 ± 34.09 (44.20) | 100.00 | 0.00 | 0.00 |
| 9 | 139.04 ± 5.36 ( 3.86) | 93.41 | 6.59 | 0.00 |
| 12 | 166.33 ± 235.23 (141.42) | 64.18 | 22.75 | 13.07 |
| 15 | 121.07 ± 115.06 (95.04) | 50.00 | 50.00 | 0.00 |
| 18 | 122.12 ± 80.43 (65.86) | 92.63 | 7.37 | 0.00 |
| 21 | 95.59 ± 16.28 (17.03) | 100.00 | 0.00 | 0.00 |
| 30 | 87.31 ± 63.95 (73.25) | 100.00 | 0.00 | 0.00 |
| 37 | 73.31 ± 68.09 (92.88) | 100.00 | 0.00 | 0.00 |
| 45 | 82.94 ± 42.98 (51.82) | 100.00 | 0.00 | 0.00 |
| 60 | 83.49 ± 78.58 (94.12) | 100.00 | 0.00 | 0.00 |
| 75 | 126.41 ± 51.23 (40.52) | 100.00 | 0.00 | 0.00 |
| 90 | 167.46 ± 21.71 (12.96) | 100.00 | 0.00 | 0.00 |
| 120 | 64.93 ± 63.11 (97.20) | 100.00 | 0.00 | 0.00 |
| 150 | 113.09 ± 40.87 (36.14) | 100.00 | 0.00 | 0.00 |
| 180 | 107.52 ± 66.24 (61.60) | 100.00 | 0.00 | 0.00 |
| 270 | 38.86 ± 32.07 (82.53) | 100.00 | 0.00 | 0.00 |
| 360 | 144.84 ± 204.84 (141.42) | 77.41 | 22.59 | 0.00 |

## APPENDIX 2.3 CARNATION CREEK SOIL RESIDUE DATA - AMPA

SAMPLING LOCATION - UPPER WATERSHED (STATIONS 1,2,3)

| TIME (DAYS) | TOTAL RESIDUE (UGS) (0 - 30 CM CORE) | DISTRIBUTION OF RESIDUES (%) | | |
|---|---|---|---|---|
| | | 0-5 CM | 5-15 CM | 15-30 CM |
| 0 | 64.98 ± 59.49 (91.55) | 87.16 | 12.84 | 0.00 |
| 3 | 148.03 ± 99.96 (67.53) | 90.60 | 9.40 | 0.00 |
| 6 | 239.82 ± 23.98 (10.00) | 96.97 | 3.03 | 0.00 |
| 9 | 236.97 ± 214.26 (90.42) | 85.99 | 14.01 | 0.00 |
| 12 | 145.99 ± 153.54 (105.18) | 56.58 | 43.42 | 0.00 |
| 15 | 320.34 ± 123.41 (38.52) | 93.27 | 6.73 | 0.00 |
| 18 | 369.90 ± 176.29 (47.66) | 85.80 | 14.20 | 0.00 |
| 21 | 448.62 ± 270.28 (60.25) | 82.08 | 12.51 | 5.40 |
| 24 | 391.57 ± 187.21 (47.81) | 87.74 | 11.01 | 1.26 |
| 27 | 363.23 ± 252.93 (69.63) | 90.59 | 9.41 | 0.00 |
| 30 | 307.27 ± 128.93 (41.96) | 98.73 | 1.27 | 0.00 |
| 37 | 426.39 ± 136.46 (32.00) | 88.64 | 11.36 | 0.00 |
| 45 | 255.44 ± 42.02 (16.45) | 94.12 | 5.88 | 0.00 |
| 60 | 240.43 ± 40.75 (16.95) | 92.69 | 7.31 | 0.00 |
| 75 | 359.93 ± 233.64 (64.91) | 96.55 | 3.45 | 0.00 |
| 90 | 320.98 ± 80.12 (24.96) | 92.71 | 7.29 | 0.00 |
| 120 | 347.99 ± 38.65 (11.11) | 61.66 | 38.34 | 0.00 |
| 150 | 588.14 ± 230.23 (39.15) | 76.28 | 17.02 | 6.70 |
| 180 | 359.84 ± 140.37 (39.01) | 77.87 | 22.13 | 0.00 |
| 270 | 284.75 ± 221.38 (77.75) | 68.71 | 18.05 | 13.24 |
| 360 | 248.96 ± 100.47 (40.36) | 98.03 | 1.97 | 0.00 |

# OFF-TARGET DEPOSIT MEASUREMENTS AND BUFFER ZONES REQUIRED AROUND WATER FOR VARIOUS AERIAL APPLICATIONS OF GLYPHOSATE

N. Payne. J. Feng. P. Reynolds
Forest Pest Management Institute
Canadian Forestry Service
Government of Canada
P.O. Box 490
Sault Ste. Marie. Ontario
P6A 5M7

## ABSTRACT

An investigation was conducted to quantify off-target deposit from three types of aerial glyphosate use-strategies for forestry use, and to estimate the width of buffer zones required around water to protect fish and their food supply from direct toxicological effects. To overcome the difficulty of estimating different buffer widths to meet the various conditions encountered, e.g., windspeed, boundary layer stability, active ingredient application rate, etc., a realistic worst case scenario was chosen, and data were collected accordingly. Glyphosate applications were made by helicopter, using three types of dispersal system, a MICROFOIL BOOM, a Thru Valve Boom and a D8-46 hydraulic nozzle. Airborne glyphosate and off-target deposits on water and foliar surfaces were measured at various downwind distances up to 200 m from multiple swaths overlaid on a crosswind track. Using these measurements, calculations were made to predict glyphosate deposits on water surfaces downwind of multiple swath applications with the use-strategies tested. Based on published measurements of the toxicity of ROUNDUP to salmon, rainbow trout and various aquatic invertebrates, an estimate was then made of buffer widths required around water bodies to keep mortality at an acceptable level. In general, measured airborne glyphosate and off-target deposit was highest from the D8-46 application, and lowest from the MICROFOIL BOOM application. In all applications off-target deposit on water decreased rapidly with downwind distance. A buffer width of 25 m around water bodies is adequate to protect salmon, rainbow trout and aquatic invertebrates from significant direct effects resulting from off-target ROUNDUP deposits from the MICROFOIL and Thru Valve Boom use-strategies; for the D8-46 use-strategy, a 30 m buffer width is required.

## INTRODUCTION

Glyphosate (N-(phosphonomethyl) glycine) is a broad spectrum herbicide that is effective in controlling deep-rooted perennial species, and also annual and biennial broad-leaf, grass and sedge species (WSSA 1983). The isopropylamine salt of glyphosate forms the active ingredient (a.i.) of the herbicide ROUNDUP (Monsanto, St. Louis, MO), which is registered in Canada for forestry use. The toxicity of ROUNDUP (now Vision®) to fish and aquatic arthropods (Folmar et al. 1979) has led the federal Department of Fisheries and Oceans and the Environmental Protection Service of Environment Canada to raise objections to its use near water bodies because of the possibility of fish mortality caused by an overspray, or the drifted cloud.

The need to minimize the hazard posed by ROUNDUP to fish and aquatic arthropods is particularly acute in the coastal region of British Columbia, where fertile alluvial sites are adjacent to salmon-bearing rivers. By maintaining a minimum distance of approach, or buffer zone, between a pesticide application and water body, the unwanted side-effects from a herbicide application can be reduced. The present investigation was conducted to quantify off-target deposit from aerial ROUNDUP use-strategies suitable for use in the mountainous B.C. terrain and to estimate the buffer width required to prevent significant mortality in populations of salmon and trout. This investigation addresses the problem of protecting fish and aquatic species from direct toxicological effects: the problem of assessing the buffer width required to protect riparian vegetation remains. To estimate the buffer width required to protect riparian and other vegetation requires measurements of the phytotoxicity of sub-lethal glyphosate deposits, as yet unknown, but the subject of an investigation in progress. Because of the phytotoxic nature of glyphosate, the buffer width required to protect vegetation may be larger than that required to protect fish and aquatic species from direct effects.

## PROBLEM ANALYSIS

The use of buffer zones enable environmental impact to be controlled, however, they should not be unnecessarily wide, because this impedes efficient forest management. The buffer width required to protect a sensitive area varies according to many factors, including the state of the atmospheric boundary layer (Pasquill 1974), structure of the plant canopy (Thom 1975), dropsize spectrum of the spray cloud and its release height (Pasquill 1974), volume and active ingredient application rates, and the number and spacing of swaths applied. The physical and biological characteristics of the buffered water body, e.g. still or flowing water, water depth, fish species present, also affect buffer width. In this investigation buffer width estimation was based on the assumption that, where possible, worst case conditions should be used. The use of a worst case scenario resolves the problem of defining and regulating buffer zones with many different widths, because conditions are chosen to give the widest buffer needed to limit the unwanted effects of the herbicide to an acceptable level.

To estimate the widths of buffer zones required around water bodies to protect fish and aquatic invertebrates during operational ROUNDUP applications, it is necessary to know how much a.i. is deposited on the water surfaces and its biological effect. Because a.i. deposit and biological effect diminish with distance from the spray application, at a certain distance from the application the environmental impact becomes negligible, i.e., comparable with natural influences. A buffer can be estimated from this distance. This technique for buffer estimation was devised and first used in estimating buffers required during applications of the insecticide permethrin (Payne et al. 1986; 1988). The problem of estimating the buffer width required around water was split into four parts. First, measurements were made of the amount of glyphosate deposited on water surfaces at various downwind distances from a single crosswind swath. Second, using the experimental data obtained for a single swath, glyphosate deposit from a multiple swath application was calculated. Third, calculated glyphosate deposits were converted into corresponding ROUNDUP concentrations, assuming uniform a.i. mixing in various water depths. Finally, buffer widths were estimated, using published measurements of the toxicity of ROUNDUP to fish and aquatic invertebrates.

Pesticide applications may require upwind, crosswind and downwind buffers. However, drops can be transported over greater distances by advection than by atmospheric diffusion or aircraft vortices (Payne et al. 1986). The largest buffer width is therefore required in the downwind direction, and this can safely be used for an upwind or crosswind buffer. This investigation addresses the problem of setting downwind buffer widths.

The dropsize spectrum of the spray cloud affects the proportion of spray deposited off-target during a pesticide application. In considering the effect of dropsize on the dispersal and deposition of a spray cloud, the spectrum can be viewed as comprising two dropsize ranges, large and small. These two size ranges are distinguished by comparing the magnitude of the drop sedimentation velocities with the standard deviation of vertical windspeeds in the atmospheric boundary layer. The physical significance of this classification is that small drop dispersal and deposition can be considered, to a first approximation, to be independent of sedimentation velocity and dependent only on meteorological variables, e.g. atmospheric stability or windspeed; plant canopy variables, e.g. canopy height, or plant density; and spray application variables, e.g. cloud release height, or tank mix volatility. For large drops the effect of the sedimentation velocity on dispersal and deposition may not be ignored, but allows large drop behavior to be viewed in terms of ballistics, with some spreading of the cloud about its centre of mass, caused by atmospheric diffusion (Pasquill 1974). The magnitude of the standard deviation of vertical windspeed in the atmospheric boundary layer varies according to atmospheric stability, geostrophic windspeed, and height above ground. Typical values are ¼-½ m/s, which provides an upper size limit of 100 to 150 $\mu$m for small drops. ULV insecticide applications generally use small drops, whereas herbicide applications generate both large and small drops (Matthews 1979). Because small drops may be transported further by the atmosphere than large drops, drift of small drops is often considered to be of greater importance in causing off-target deposit.

## Worst Case Analysis

The worst case described below applies to off-target deposit on water bodies resulting from small drop drift. The variables considered in choosing a worst case were those affecting the amount of a.i. deposited on water downwind of the herbicide application.

### Spray cloud dispersal experiment

For the experimental part of the study these variables fall into three categories, those related to meteorology, plant canopy, and spray application variables. However for reasons of data utility, a number of the plant canopy and spray application variables were set in accordance with operational conditions rather than the worst case.

The meteorological variables that affect spray cloud dispersal are atmospheric boundary layer stability, windspeed, relative humidity and air temperature. The influence of atmospheric stability lies in its effect on windspeed and turbulence, through its enhancement or damping of vertical mixing (Thom 1975). Atmospheric boundary layer stabilities are categorized as stable, unstable and neutral (Neiburger et al. 1973), according to the gradient of the vertical air temperature profile. Stable conditions are normally found at night and around dawn and dusk, unstable conditions are found during daylight hours when significant insolation occurs. Neutral conditions are usually found in overcast conditions or with high windspeeds, and for short periods near dawn and dusk (Sutton 1953). Stable conditions have been, and in regulatory circles still are, favored for minimizing drift of both large and small drops. However, Crabbe and his co-workers (Crabbe et al. 1983; Crabbe and McCooeye 1985) have shown that neutral or unstable conditions minimize small drop drift, whereas stable conditions cause increased drift beyond the treatment area.

Windspeed is another important meteorological variable affecting off-target deposit. Drop deposition on a water surface occurs at a rate proportional to the drop concentration in the air above (Pasquill 1974). Increased windspeed reduces drop concentration near the ground (Crabbe and McCooeye 1985; Joyce et al. 1981); this is partly because drop impaction efficiency increases with windspeed (May and Clifford 1967). The worst case for drop deposition on a water surface is, therefore, to spray in light winds, but not calm conditions.

Relative humidity (r.h.) is also influential if water-based sprays are used (Green and Lane 1964). Drop impaction efficiency increases with drop diameter (May and Clifford 1967), thus drift will increase if dropsizes are reduced because the spray cloud will be deposited more slowly. Because r.h. is inversely related to drop evaporation rate (Rogers 1979), the worst case is to use low r.h. values in the range normally encountered while spraying. Increased air temperature increases drop evaporation rate (Green and Lane 1964; Rogers 1979), and thus reduces dropsizes and impaction efficiencies, causing increased drift. The worst case is, therefore, to use a high air temperature in the range encountered while spraying. In summary the worst case meteorological conditions for small drop drift include a stable boundary layer, light wind, low r.h. and high air temperature.

Plant canopy variables also have an effect on off-target deposit by modifying the atmospheric boundary layer and filtering the spray cloud. The significant variables include canopy height, density (plants/m ) and plant type, i.e. deciduous or coniferous. The effects of plant canopy variables are discussed further by Payne et al. (1986). The canopy selected in this investigation was typical of those requiring herbicide treatment in the coastal regions of British Columbia, and was therefore of operational relevance, but being aerodynamically rough did not provide a worst case.

The spray application variables influencing dispersal include the dropsize spectrum and release height of the spray cloud, the volume and a.i. application rate, the tank mix volatility and the number and spacing of swaths. Dropsize spectra are determined by the choice of atomizer and settings, the air-speed past the atomizer and the physical characteristics of the tank mix. All of these variables were set according to the use-strategies tested. Spray cloud release height was low, in accordance with operational practice. However this release height also provides a worst case for spray deposited on water surfaces, because mixing and dilution of the spray cloud increases with release height, and spray deposit on water is proportional to drop concentration in the air above. Volume application rates ranged between 90 and 230 L/ha, also in accordance with operational practice for a canopy of the height and density treated. The tank mix diluent was water, which provides a worst case for tank mix volatility because of its relatively high vapor pressure compared to other diluents used in operational spray applications (Matthews 1979; Riddick and Bunger 1970). A high volatility tank mix causes fast drop evaporation, which in turn decreases dropsize and impaction efficiency, resulting in greater drift than from low volatility tank mixes. Swath width was also set in accordance with operational practice.

### Modeling glyphosate deposit from multiple swath applications

A worst case was also chosen for modeling deposit from multiple swath applications. Off-target deposit downwind of a multiple swath application increases with the total amount of a.i. sprayed, which depends on the a.i. application rate and the size of treatment area. The glyphosate application rate was 2.1 kg acid equivalent (a.e.)/ha, the maximum recommended rate in Canadian forestry. The swath number was also worst case, based on a 100 ha (1 x 1 km) area, which is at or near the upper limit for size of treatment area for glyphosate applications in Canadian forestry.

## EXPERIMENTAL METHODS

### Site and Canopy

The experiment was conducted on a nearly flat area in the Skeena River Valley, near grid reference 129°23'W, 54°19'N (Fig. 1). With the wind direction chosen for the spray trials, i.e. up-valley and approximately SW, there was an upwind fetch of nearly flat terrain about 1 km long, bearing a largely deciduous forest with a canopy 10-30 m in height. Upwind of this was a fetch of about 3 km comprising wooded floodplain and open water. Over this distance the valley floor was at least 2.5 km wide. Wind directions suitable for the trials were restricted to up and down the valley because of the lee eddies caused by air flow over mountains which results in irregular and atypical spray cloud dispersal (Atkinson 1981; Scorer 1978).

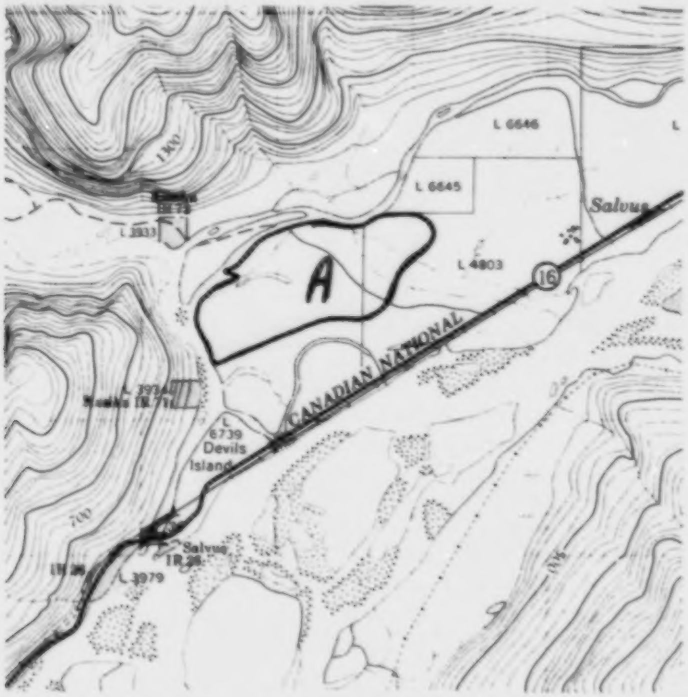


Figure 1. Experimental site location (A) in Skeena river valley (1:50,000 map 103-I/6, Salvus).

The spray site was a 1968-69 cutover, which bore a largely deciduous canopy. Canopy composition and tree heights were measured at five locations, 100 m apart, along a transect across the site. At each location all trees within a circular area with radius 10 m were counted, and the heights of ten randomly selected trees were measured. The results are given in Table 1.

### Meteorological Measurements

On-site meteorological measurements were used to select suitable spraying conditions and to characterize conditions during the spray application and dispersal. Windspeed was measured at 13 and 22 m above ground level (agl), with cup anemometers (threshold speed 0.34 m/s, Heathkit digital weather computer Model ID-4001, Heath Co., Benton Harbour, MI). At 13 m agl the lower

Table 1. Plant canopy composition

| Tree species | Plant density (Avg stems/ha) | Plant height (m. Avg ± SD) |
|---|---|---|
| Red Alder<br>(*Alnus rubra* Bong) | 1318 | 17.3 ± 4.3 |
| Black Cottonwood<br>(*Populus trichocarpa* Torr. & Gray) | 146 | 27.3 ± 2.1 |
| Bebb's willow<br>(*Salix bebbiana* Sarg.) | 1236 | 9.7 ± 2.2 |

anemometer was just above the canopy. Measured windspeeds were corrected to provide true wind speeds, using calibration curves. Wind direction was measured at 22 m agl (wind vane, Heathkit digital weather computer ID-4001). Air temperatures were measured at 13 and 22 m agl with diode type sensors (Heathkit digital weather computer) shaded to prevent direct heating by solar or terrestrial radiation. Relative humidity was measured at 2 m agl (capacitance type hygrometer, Heath Co.) during the spray application and dispersal. Meteorological measurements were manually recorded at half minute intervals during the spray application and dispersal, a period of up to 20 min. Meteorological conditions during the trials (Table 2) provided the worst case conditions required to maximize glyphosate deposit on downwind water bodies from small drop drift.

Table 2. Meteorological measurements during spray applications and dispersal

| Trial number | 1 | 2 | 3 |
|---|---|---|---|
| Date of trial | 19/9/84 | 30/9/84 | 30/9/84 |
| Time spraying commenced | 1915 | 1630 | 1920 |
| Time of Sunset (PST) | 2046 | 2022 | 2022 |
| Windspeed @ 13m agl (avg ± SD m/s) | 0.4 ± - | 0.5 ± 0.2 | 0.4 ± 0.1 |
| Windspeed @ 22m agl (m/s) | 0.8 ± 0.3 | 0.9 ± 0.3 | 0.6 ± 0.3 |
| Air temperature @ 13m agl (avg. °C) | 8 | 15 | 11 |
| Air temperature @ 22m agl (°C) | 10 | 16 | 12 |
| Stability of lowest 20m of atmosphere | Stable | Stable | Stable |
| Relative humidity (avg. %) | 80 | 76 | 88 |

**Spray Applications**

Three use-strategies were tested, including two designed during this investigation to provide low off-target deposits (Microfoil and Thru Valve Boom ) and another widely used by the USDA Forest Service (D8-46). A helicopter was chosen for all applications because of its maneuverability, and hence its suitability for applying pesticide in mountainous terrain, such as that in the B.C. coastal region. Different dispersal systems were used in each trial, but spray cloud release heights, and meteorological conditions were similar in all.

The application in trial 1 was made with a MICROFOIL BOOM (Rhone Poulenc, Lansdale, PA). This dispersal system was designed to provide good drift control by minimizing the proportion of small drops generated. The glyphosate and volume application rates were 3.4 kg a.e./ha and 230 L/ha per swath. The chosen a.i. application rate provided detectable residues at the sampling stations furthest downwind, however the results presented were adjusted to the maximum recommended rate in Canadian forestry. The volume application rate is representative of operational herbicide applications in which a dense multi-storey plant canopy is treated. The MICROFOIL BOOM was 7.9 m long, and carried 52 hayrake nozzles at 0.15 m intervals. The hayrake nozzles were fitted with 2.4 mm restricting orifices and comprised 10 jets (I.D. 1.5 mm), oriented backwards to minimize relative fluid velocities. The dispersal system was forward-mounted on a Bell 47-T helicopter, and flown at 11 m/s at about 3 m above canopy height, using a boom pressure of 137 kPa, giving a total flow rate of 200 L/min. The planned swath width was 13 m, and the tank mix sprayed was a 4.2% v/v mixture of ROUNDUP and water. The chosen flying speed and boom pressure fall within the recommended range for minimum drift. From a previous study (van Vliet et al. 1988) the dropsize spectrum in trial 1 was estimated to have volume and number median diameters of about 3000 and 2700 microns at release, with 4% of drops having diameters less than 1600 microns, representing 0.63% of the spray volume.

Swath-length and number were an important consideration in the design of the spray trials. Measurements of average spray deposit from a single swath were required for modelling. In each trial several swaths were overlaid along a crosswind track to reduce deposit variability and provide sufficient a.i. for detection at the sampling stations furthest downwind. Swath lengths were sufficient to make the application representative of an infinite line source at the downwind distances where deposits were sampled (Payne 1983), and thus provide worst case deposits. In trial 1 three swaths 300 m in length were applied. The volume application rate used in trial 1 is relatively high and consequently the work rate is low, making this type of application expensive for operational use.

The application in trial 2 was made with a Thru Valve Boom (TVB, Waldrum Specialties, Ambler, PA). The TVB is also designed to provide good drift control by minimizing the proportion of small drops generated. A.i. and volume application rates were 2.2 kg a.e./ha and 91 L/ha per swath. The TVB was 9.1 m long and carried 62 burr nozzles at 0.15 m intervals. The burr nozzles were fitted with 2.03 mm restricting orifices and comprised 15 jets (I.D. 1.1 mm) oriented backwards to reduce relative fluid velocity. The TVB was forward-mounted on a Bell 47-T helicopter and flown at about 20 m/s at about 3 m above the canopy height, using a boom pressure of 171 kPa, giving a total flow rate of 165 L/min. The planned swath width was 15 m, and the tank mix sprayed was a 6.7% v/v mixture of ROUNDUP and water. From a previous study (van Vliet et al. 1988) the dropsize spectrum in trial 2 was estimated to have volume and number median diameters of about 1000 and 150 microns at release, with about 30% of drops having diameters less than 100 microns, representing 0.04% of the spray volume at release. In trial 2 five swaths 300 m long were applied. As used in trial 2 the TVB provides lower volume application rates and consequently higher work rates than the MICROFOIL BOOM configuration employed in trial 1. However the volume rate is still relatively high for glyphosate applications in Canadian forestry.

The application in trial 3 was made with a D8-46 hydraulic nozzle, and employed a use-strategy used in USDA Forest Service herbicide applications. A.i. and volume application rates were 2.1 kg a.e./ha and 90 L/ha per swath respectively. The boom was 8.5 m long and carried 32 hollow cone nozzles (disc number 8, 46 whirlplate), evenly spaced along the boom and oriented backwards to reduce relative fluid velocity. The dispersal system was mid-mounted on a Bell 47-T helicopter and flown at about 20 m/s at 3 m above canopy height, using a boom pressure of 171 kPa, giving a total flow rate of 163 L/min. The planned swath width was 15 m, and the tank mix sprayed was a 6.5% v/v mixture of Roundup and water. From a previous study (Yates et al. 1985) the drop-size spectrum was estimated to have volume and number median diameters of about 460 and 70 microns respectively at release, with about 60% of drops having diameters less than 100 microns, representing 1% of the spray volume. In trial 3 four swaths 300 m long were applied.

## Off-target Deposit and Airborne Glyphosate Measurements

### Sampling methods

The layout of the experimental site is shown in Figure 2; swaths were laid along a NW-SE crosswind track (B), and sampling stations (C) were set up at downwind distances of 25, 50, 75 100 and 200 m.

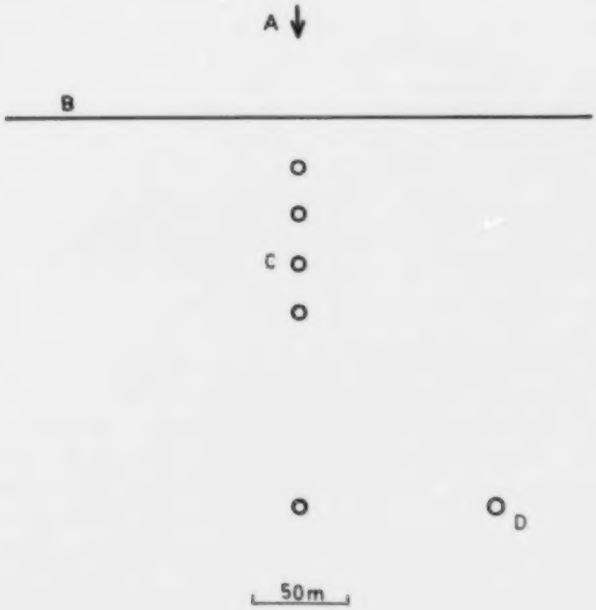


Figure 2. Experimental layout (to scale), with planned wind direction (A), 300 m crosswind track (B), sampling stations (C) and meteorological station (D).

Because average wind directions during the trials were within 20° of the planned direction, the downwind distances of the sampling stations were within 6% of the planned values, and consequently no corrections were applied. Clearings 8 m in diameter (50% canopy height) were made around each sampling station to reduce local interception of the spray cloud by the canopy and expose the collectors to ensure maximum deposition, and provide worst case deposits.

Glyphosate deposit on imitation water and foliar surfaces and airborne glyphosate were measured. Off-target glyphosate deposit was sampled at all stations with collectors comprised of a polyethylene sampling sheet (0.3 x 1 m) placed on a larger polyethylene sheet (2 x 2 m), pegged over an area cleared of vegetation. These collectors were aerodynamically similar to a water surface and thus the airflow over them was similar to that over water. Spray deposits on a water surface and the collector were therefore assumed to be similar. At the 25, 50 and 75 m stations one sheet was exposed and at the remaining stations the sampling area was doubled. To prevent contamination in the second and third trials a backing sheet was placed beneath the sampling sheet. Glyphosate deposits on the sampling sheet were quantified.

Off-target glyphosate deposits at the 50, 100 and 200 m stations were sampled with collectors comprised of a red alder branch on which the upper and lower surfaces of ten randomly chosen leaves were covered with a polyethylene sheet, cut to match the leaf shape. Red alder was chosen as a common weed species in B.C. herbicide applications. At each station an apical branch was mounted vertically at the canopy top, and a dorsal branch was mounted horizontally at 2 m agl, using light-weight sampling masts (Beveridge and Payne 1986). Glyphosate deposits on the polyethylene leaf covers were quantified, and their areas were measured with a polar planimeter (Davis and Kelly 1967).

Measurements of airborne glyphosate were made at the 50, 100 and 200 m sampling stations using Rotorod samplers (Ted Brown Associates, 26338 Esperanza Drive, Los Altos Hills, CA 94022), which collect drops by inertial impaction (Fig. 3). Based on measurements of impaction efficiency (May and Clifford 1967), these devices were assumed to collect all drops in the volume of air sampled. The glyphosate deposit on the Rotorod collecting surface is proportional to the concentration of airborne glyphosate (May _et al_. 1976). Because glyphosate has a very low vapor pressure (WSSA 1983), airborne a.i. is largely contained within spray drops and vapor sampling is unnecessary. Drops were collected on two teflon cylinders (O.D. 2.6 mm) mounted on 'U' rods. Two samplers were deployed at each station supported on the sampling masts, with one at canopy top, and the other at 2 m agl. Glyphosate deposits on the teflon cylinders were quantified.

All collectors were exposed for up to 20 min after the spray application was completed to allow the spray cloud to be advected over all sampling stations, and for drops to penetrate the plant canopy and be deposited. Samples were then collected and stored at about -10°C until deposits were quantified.

### Glyphosate quantification

Spray deposits were washed from collecting surfaces with 0.1N hydrochloric acid by sonication and mechanical agitation. The rinsings from the ground sheets were cleaned-up with anion- and cation-exchange columns, according to the method described by Cowell _et al_. (1986). Samples were then filtered (Milipore SLHV 025 NS filter) and the residues of glyphosate and its principal metabolite aminomethyl-phosphonic acid (AMPA) were quantified by high performance liquid chromatography. Detection and derivatisation were carried out using a methodology developed by Monsanto (1983, unpublished report). The chromatograph was fitted with a variable wavelength UV/vis light detector and a ninhydrin post-column reactor. Glyphosate and AMPA residues were quantified by

Figure 3. Rotorod sampler with 'u' rod and teflon collectors.

measuring peak heights of detector response, which were then interpreted by comparison with analytical standards injected after every second sample. With this method the limit of quantification for glyphosate was about 500 ng, while that for AMPA was about 150 ng. AMPA comprised less than 6% of the glyphosate residue in any sample.

## Estimating Buffer Width

The technique for estimating buffer widths required around pesticide applications described by Payne et al. (1988) has been applied in the present investigation. The total a.i. deposited on water bodies downwind of a multiple swath application was calculated by adding the contributions from individual swaths using a computer program. The deposit-distance relationships were based on the measurements of average glyphosate deposit from a single swath with an a.i. application rate of 2.1 kg/ha. Interpolation and extrapolation were made by assuming that glyphosate deposit on water surfaces varied according to the equation:

$$J = A\, x^{B} \qquad (1)$$

where J is glyphosate deposit ($\mu g/m^2$), x is downwind distance from the swath and A and B are constant for a given use-strategy. Equation (1) is often used to describe deposit-distance relationships beyond the distance of maximum deposit (Pasquill 1974; Sutton 1953).

The calculations required extrapolation of the off-target deposit measurements from a downwind distance of 200 m to about 1 km; this was done using the curve (equation 1) fitted to the measurements at 100 and 200 m downwind. This extrapolation provides worst case spray deposits for two reasons. First, the spray lines are subject to crosswind spreading by atmospheric diffusion. This lateral broadening will dilute the cloud and reduce airborne drop concentrations and hence spray deposit. Second, the cloud is winnowed as it moves downwind because inertial impaction efficiency increases with dropsize, depositing large drops faster than small drops. As a result the average deposition velocity of the cloud is reduced and actual spray deposit will be less than the extrapolated value.

Buffer widths were estimated as follows. Using the mathematical model, glyphosate deposit was calculated at various downwind distances from a 100 ha (1 x 1 km) spray application, assuming operational swath widths. The predicted glyphosate deposit was then converted to a glyphosate concentration in water by assuming complete and even mixing in various water depths, with no further dilution. This assumption is worst case because glyphosate is rapidly adsorbed onto suspended particulate matter, which reduces its availability to aquatic organisms (Tooby 1985); also the salmon and trout populations requiring protection are usually in flowing water, which causes dilution. Buffer widths were estimated from the downwind distance at which the predicted glyphosate concentration fell below an acceptable level.

## RESULTS AND DISCUSSION

### Airborne Glyphosate and Off-target Deposit Measurements

Table 3 presents measurements of glyphosate deposit ($\mu g/m^2$) collected by Rotorod samplers at various downwind distances from a single crosswind swath with an a.i. application rate of 2.1 kg a.e./ha. Figures 4 (a) and (b) show measurements of glyphosate deposit ($\mu g/m^2$) on ground sheets and leaf covers, at various downwind distances from a similar application. The measurements represent the average deposit from a single swath. Actual measurements were adjusted to correspond to this a.i. application rate, in addition, measurements of glyphosate deposit on the leaf covers and teflon collecting surfaces at canopy top and at 2 m agl were averaged. The mean ratio of glyphosate deposit on leaf covers at canopy top to that at 2 m agl was 1.24 (S.D. = 1.00, n = 9), indicating that average deposit increased with height above ground.

The results in Table 3 and Figures 4 (a) and (b) indicate that the lowest airborne glyphosate concentrations and off-target deposits were from the Microfoil application and the highest were from the D8-46 application. These measurements are consistent with the dropsize spectra statistics presented above, which indicate that the spray volume in drops with diameters less than 100 microns was greatest in the D8-46 application, and least in the Microfoil application. Glyphosate residues collected by Rotorods at 50 m in trial 1 were lower than those in trials 2 and 3 by factors of 5 and 35 respectively, and that collected at 200 m from the swath was unquantifiable (<200 ng) in trials 2 and 3. The measured glyphosate deposit on teflon collectors at 200 m in trial 1 is anomalous. In trials 1 and 2 glyphosate deposits on ground sheets were higher than those on leaf covers, but this was not the case in trial 3. This difference is caused by differences in dropsize spectra, in particular the smaller proportion of large drops in trial 3.

Table 3. Glyphosate deposits on teflon collectors at various downwind distances from a single crosswind swath at 2.1 kg a.i./ha

| Downwind distance (m) | Glyphosate deposit ($\mu g/m^2$) Trial 1 | 2 | 3 |
|---|---|---|---|
| 50 | 380 | 1960 | 13400 |
| 100 | 103 | 195 | 536 |
| 200 | 130 | < 71 | < 71 |

Glyphosate deposits on ground sheets in trial 1 (Microfoil) were 10 to 100 fold lower than in trials 2 (TVB) and 3 (D8-46), at distances of 75 m and less from the track. However, by 200 m downwind the glyphosate deposits on ground sheets in trials 1 and 2 were similar and approximately half the amount found in trial 3. Glyphosate deposits on leaf covers 50 m downwind of the Microfoil application were 10 to 50 fold lower than that measured from the other two applications. In contrast to the glyphosate deposits on ground sheets, large differences in foliar glyphosate deposit were found at 200 m downwind. The foliar deposit at 200 m in trial 1 is anomalously large.

## Off-target Deposit from Multiple Swath Applications

Calculated glyphosate deposits on water surfaces downwind of multiple swath ROUNDUP applications at 2.1 kg a.e./ha are presented in Figure 5. For the TVB and D8-46 results extrapolation beyond 200 m was made using exponent (B) obtained from the Microfoil extrapolation, because the exponents derived for the TVB and D8-46 trials would have given quicker attenuation of deposit than for the Microfoil trial. In view of the proportions of spray volume in drops with diameters less than 100 microns, this was thought to be an unrealistic assumption. No extrapolation was made upwind of the 25 m sampling station because of swath displacement (see below). Table 4 shows the downwind distances from the closest swath by which calculated glyphosate deposit on water surfaces from a 100 ha application falls to 0.1, 1, or 5% of the maximum recommended a.i. application rate, i.e. 210, 2100 and 10,500 $\mu g/m^2$.

## Effect of Off-target on Fish and Aquatic Invertebrates

The effect on fish and aquatic invertebrates of glyphosate deposits from a 100 ha application was assessed using toxicological data from several published studies. ROUNDUP toxicity to fish has been measured by EVS Consultants in static tests for Monsanto (1986a-d), using coho and chinook salmon smolt (*Oncorhynchus kisutch & O. tshawytscha*) and rainbow trout fry (*Salmo gairdneri*). The tests showed that following a 10 d exposure to ROUNDUP in fresh water at concentrations up to 3.2 mg/L, coho salmon smolts were capable of survival and adapting to seawater. Static tests gave measured 96 h ROUNDUP LC$_{50}$ s of 22.4, 20 and 26 mg/L respectively for coho and chinook salmon and rainbow trout. Fish mortalities of less than 10% were reported for ROUNDUP concentrations up to 6.6 mg/L.

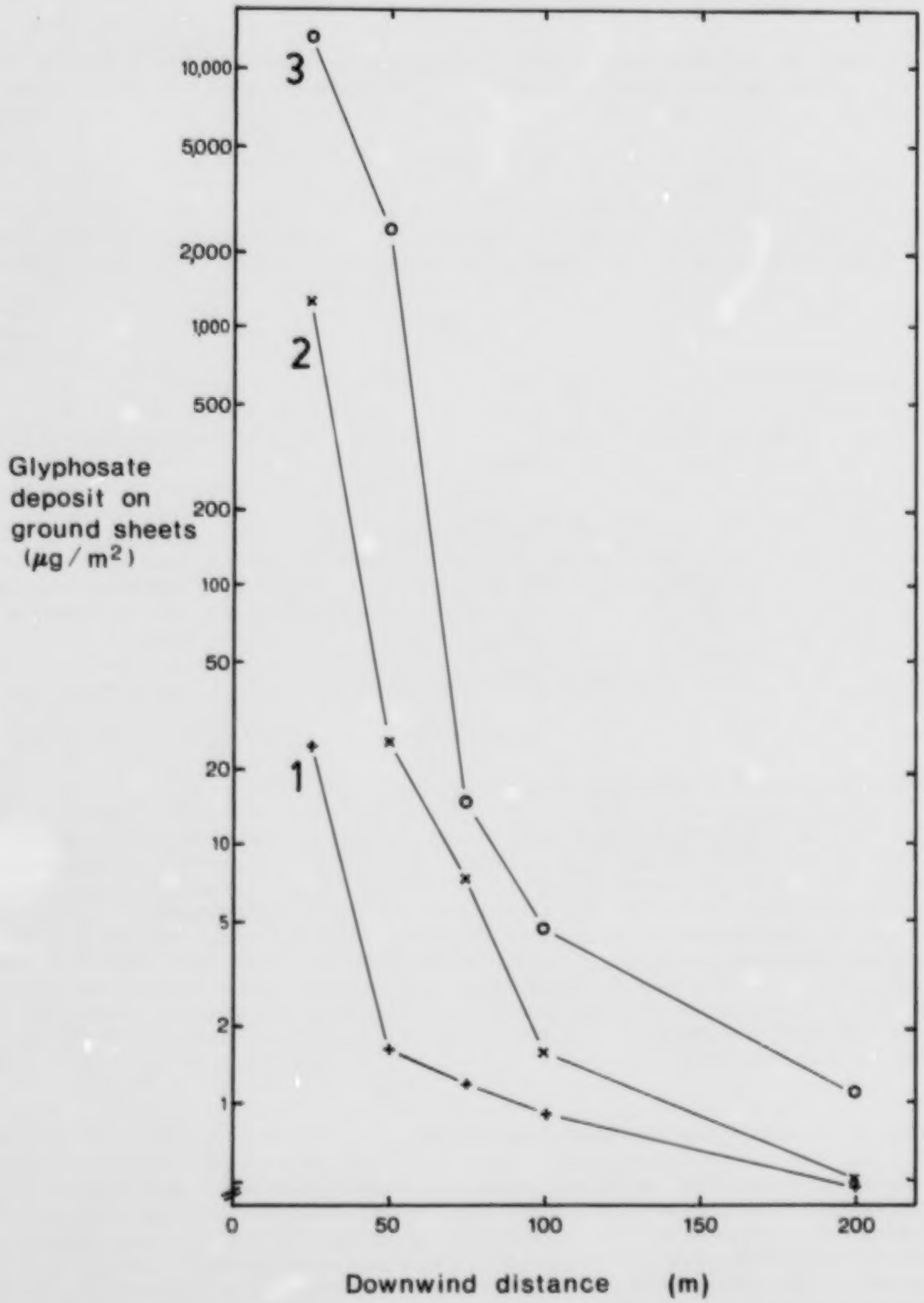


Figure 4. (a). Glyphosate deposit on ground sheets downwind of a single crosswind swath at 2.1 kg a.i./ha. Labels 1, 2 and 3 denote trial numbers.

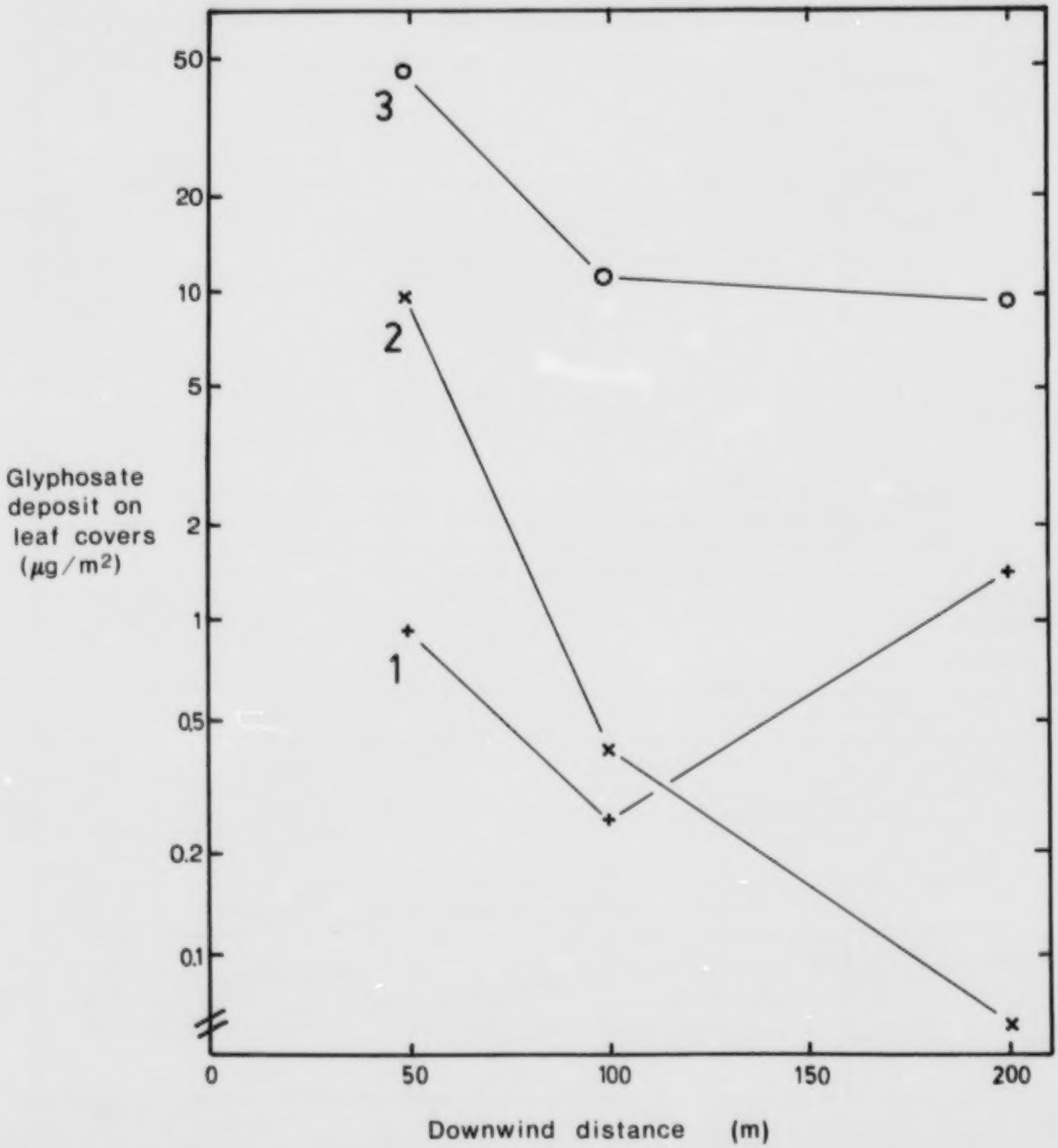


Figure 4. (b). Glyphosate deposit on leaf covers downwind of a single crosswind swath at 2.1 kg a.i./ha. Labels 1, 2 and 3 denote trial numbers.

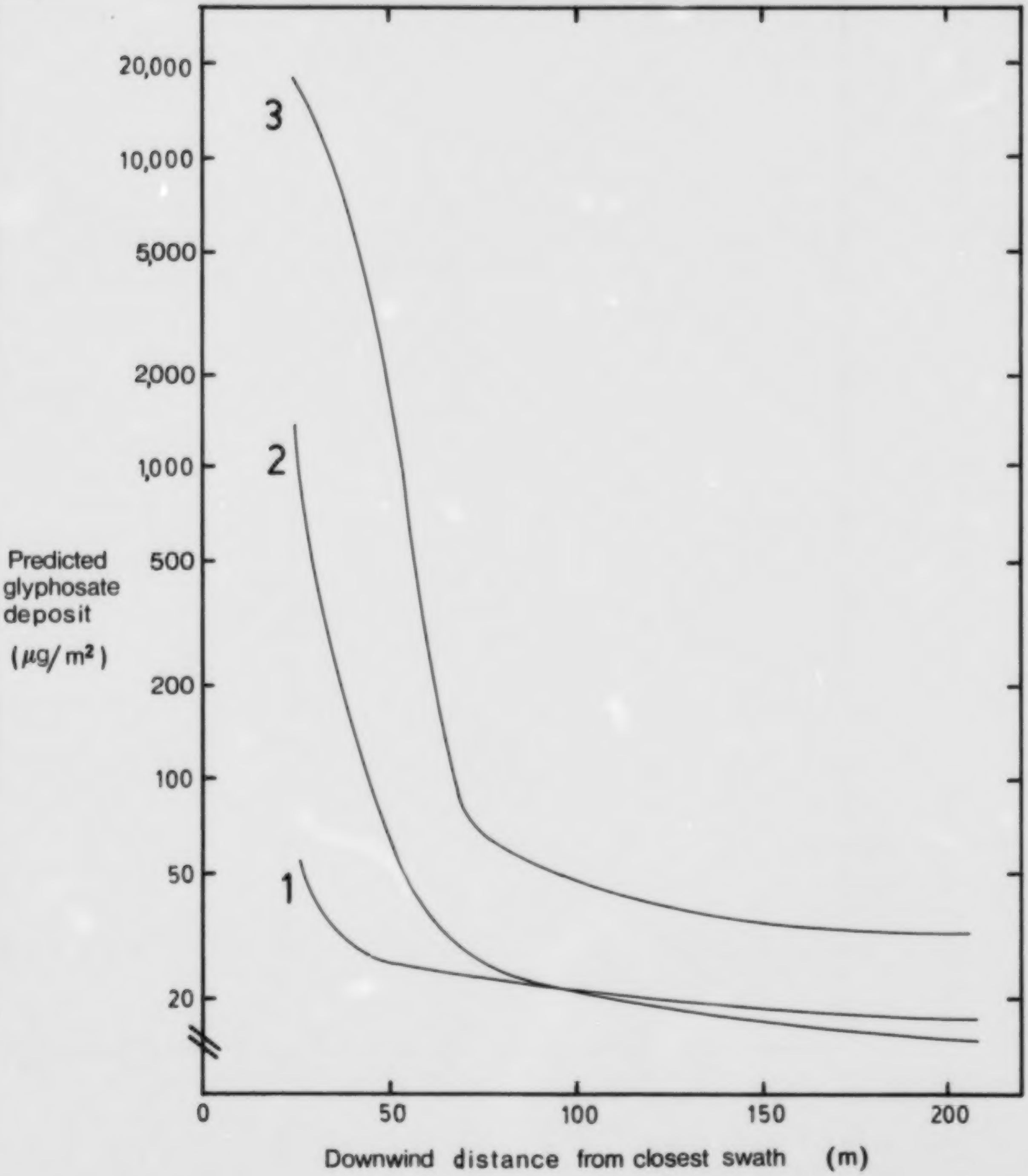


**Figure 5.** Calculated glyphosate deposit on water surface downwind of 100 ha application at 2.1 kg a.i./ha. Labels 1, 2 and 3 denote trial numbers.

Table 4. Distances from 100 ha application by which calculated glyphosate deposit on water surfaces falls to various percentages of maximum recommended a.i. application rate

| Glyphosate deposit as percentage of 2.1 kg/ha (%) | Downwind distance from closest swath (m) | | |
|---|---|---|---|
| | Microfoil | TVB | D8-46 |
| 5 | < 25 | < 25 | 28 |
| 1 | < 25 | < 25 | 49 |
| 0.1 | < 25 | 35 | 62 |

Hildebrand et al. (1982) studied the effects of ROUNDUP on fingerling rainbow trout populations, and reported 96 h $LC_{50}$ s of 52 and 54.8 mg/L respectively from field and laboratory bioassays. ROUNDUP was also applied manually to shallow forest streams in which pens containing fingerling rainbow trout (2.3 g) had been placed in water depths between 15 and 29 cm. Glyphosate application rates of 2.2, 22 and 220 kg a.e./ha were used in direct oversprays. No rainbow trout mortality occurred and no symptoms of stress or physical discomfort were observed. Glyphosate concentrations in stream water were not reported.

A study by Folmar et al. (1979) reported acute ROUNDUP toxicities from static tests on various fish and aquatic invertebrates. The 96 h ROUNDUP $LC_{50}$ s for adult rainbow trout and fathead minnow (*Pimephales promelas*) were 8.3 and 23 mg/L respectively. The rainbow trout life stage most sensitive to ROUNDUP was the fingerling (1.0 g), having a 96 h ROUNDUP $LC_{50}$ of 1.3 mg/L. No changes in fecundity were observed in adult rainbow trout exposed for 12 h to 2.0 mg/L. The 48 h $EC_{50}$ s (immobilizing concentration) measured for first-instar daphnids (*Daphnia magna*) and fourth-instar midge larvae (*Chironomus plumosus*) were 3.0 and 18 mg/L respectively.

Hildebrand et al. (1980) also studied the effect of ROUNDUP on daphnid (*D. magna*) populations. This abundant aquatic invertebrate forms a significant part of the diet of fish (Crosby and Tucker 1966). A manual application of ROUNDUP was made to forest ponds containing pens into which adult *D. magna* had been placed. The pens restricted the organisms to a surface layer 30 cm in depth. Glyphosate application rates of 2.2, 22 and 220 kg a.e./ha were used in a direct overspray. Survival rates exceeded 90% in all trials, and the control survival rate was similar to that obtained at 220 kg a.e./ha. Glyphosate concentrations in pond water were not reported.

Based on the EVS laboratory study cited above, a ROUNDUP concentration of 1.0 mg/L, equivalent to 0.3 mg glyphosate a.e./L, will limit mortality to less than 10% in populations of salmon smolt and rainbow trout fry. In contrast, the laboratory study by Folmar et al. (1979) indicates that a ROUNDUP concentrations of 1.0 mg/L, if maintained for 96 h, could result in about 50% mortality in the most sensitive life stage of rainbow trout. However, the studies by Hildebrand et al. (1980 & 1982) showed no rainbow trout mortality with theoretical ROUNDUP concentrations from oversprays of 249-480 mg/L, and greater than 90% survival of adult *D. magna* at theoretical ROUNDUP concentrations of 250 mg/L. For the purposes of buffer setting, a ROUNDUP concentration of 1 mg/L was chosen as the maximum tolerable level, however a more conservative limit may be argued considering Folmar's (1979) results.

## Buffer Widths

Table 5 shows the predicted ROUNDUP concentrations (μg/L) in water bodies at various downwind distances from 100 ha applications at 2.1 kg/ha with the three use strategies tested. The buffer widths required around water to limit ROUNDUP concentrations to 1 mg/L (1000 μg/L) were estimated for water depths of 0.1, 0.25 and 0.5 m. For each combination of use-strategy and water depth, the downwind distances from the final swath at which ROUNDUP concentrations fell to 1 mg/L were less than 25 m. A buffer width of 25 m is therefore adequate to limit off-target deposit from small drop drift to the chosen level for all three use-strategies tried. Extrapolation of the spray deposit data to distances less than 25 m in order to estimate a more exact buffer width is inadvisable because of swath displacement, a discussion of which follows.

Table 5. Predicted ROUNDUP concentrations (μg/L) in water body at various downwind distances from 100 ha application

| Downwind distance (m) | Trial number 1 | | | 2 | | | 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Water depth (m) | | | | | | | | |
| | 0.1 | 0.25 | 0.5 | 0.1 | 0.25 | 0.5 | 0.1 | 0.25 | 0.5 |
| 25 | 1.77 | 0.72 | 0.36 | 46 | 18 | 9.2 | 590 | 240 | 120 |
| 50 | 0.85 | 0.33 | 0.17 | 2.0 | 0.82 | 0.39 | 82 | 32 | 16 |
| 75 | 0.79 | 0.31 | 0.15 | 0.99 | 0.39 | 0.20 | 2.2 | 0.89 | 0.46 |

The model and data from this investigation can be used to estimate buffer widths for use-strategies similar to those tested, but with different a.i. application rates and areas. However, the data from this investigation are not generally applicable for use-strategies employing different dispersal systems, emission rates or airspeeds, due to differences in dropsize spectra. When measurements of the phytotoxicity of sub-lethal glyphosate deposits become available, the off-target deposit measurements from this investigation can be used to estimate buffer widths required to protect riparian and other vegetation with these use-strategies.

## Swath Displacement

It is apparent from the above discussion that buffer widths required around water bodies to protect fish and aquatic invertebrates from small drop drift are relatively small (<25 m). In light of this, the significance of large drop drift, or swath displacement must also be assessed. Swath displacement or large drop drift has been estimated for the three use-strategies tried in this investigation for worst case meteorological conditions for small and large drop drift. Windspeed is the most influential meteorological variable causing large drop drift, with higher windspeeds causing greater swath displacement. Atmospheric stability also affects swath displacement through its effect on the horizontal wind-speed profile. However for the low release heights in these trials differences caused by stability are small and were ignored in estimating swath displacement. Large drop evaporation during flight was slight for the present trials, because their lifetimes are much larger than flight times, e.g. a 200 micron diameter water drop has a lifetime of about 200s in air at 20°C with a relative humidity of 80% (Matthews 1979), compared to large drop flight times of 1-10s.

Swath displacement was estimated using ballistics (Pasquill 1974). The following simplifying assumptions were made. The large drop component of the spray cloud was represented by the volume median dropsize, and the fallspeed was chosen accordingly. Initial drop velocities were assumed to be negligible. The spray cloud was advected through the 3 m release height (above canopy), and the top third of the canopy height (1/3 x 18 m = 6 m). Windspeed inside a forest canopy increases with height, however in the lower two thirds of the canopy windspeeds are low (Oliver 1971, 1975), and therefore advection is slight. The average horizontal windspeed at canopy top was used to calculate displacement. In fact, the average horizontal windspeeds above and below this height are greater and smaller respectively than the value at canopy top, making this approximation a good one. The effect of the two counter-rotating aircraft vortices on swath displacement or large drop drift was assumed to be small due to the magnitude of drop fallspeeds, with the vortices acting to spread the cloud about its centre of mass rather than causing advection of the total cloud. Swaths were crosswind. In the microfoil application the volume median diameter (VMD) was about 3000 μm. A water drop of this size has a fallspeed of about 8.1 m/s (Rogers 1979). In the TVB and D8-46 applications the VMDs were about 1000 and 460 μm. The fallspeeds of water drops with these diameters are about 3.9 and 1.9 m/s (Hinds 1982).

At the windspeeds used for the present trials, about 1 m/s at canopy top, the swath displacements i.e. the distance from the centre of the spray deposition pattern or effective swath to the release line for microfoil, TVB and D8-46 were estimated to be 1, 2 and 4 m respectively. Under worst case conditions for large drop drift, with an average horizontal windspeed of 4 m/s at canopy top (about 16 km/h), swath displacements were estimated to be 5, 9 and 18 m respectively. It should be noted that these swath displacements refer to the large drop component of the spray cloud, and predict the average drop displacement for a release height 3 m above canopy top.

This estimate of swath displacement allows small and large drop drift to be compared. Figure 6 shows estimated swath position in relation to the release line for the three types of application used, in average horizontal windspeeds of 1 and 4 m/s. Swath widths were those described above. For the use-strategies tested a buffer of 25 m from the closest downwind swath has been shown to protect fish and aquatic invertebrates from significant direct toxicological effects of glyphosate small drop drift. However, taking large drop drift into account, it is apparent that for the D8-46 a slightly larger buffer of 28-30 m is required to prevent the swath from reaching the water body by displacement, for a release height of 3 m above canopy top. Greater release heights will result in larger swath displacements.

## Effect of Overspray

A calculation was made of the ROUNDUP concentration in water resulting from an overspray. To provide worst case deposit all a.i. was assumed to be deposited in the swath region. For a spray over still water 0.1 m deep, assuming complete and even mixing, and no further dilution, the resulting glyphosate (a.e.) concentration is 2.1 mg/L. In flowing water dilution will occur, reducing the concentration. However, the suggested acceptable value is 0.3 mg/L, indicating that an overspray with ROUNDUP at 2.1 kg a.e./ha may cause unacceptable mortality in shallow water bodies, and should be avoided.

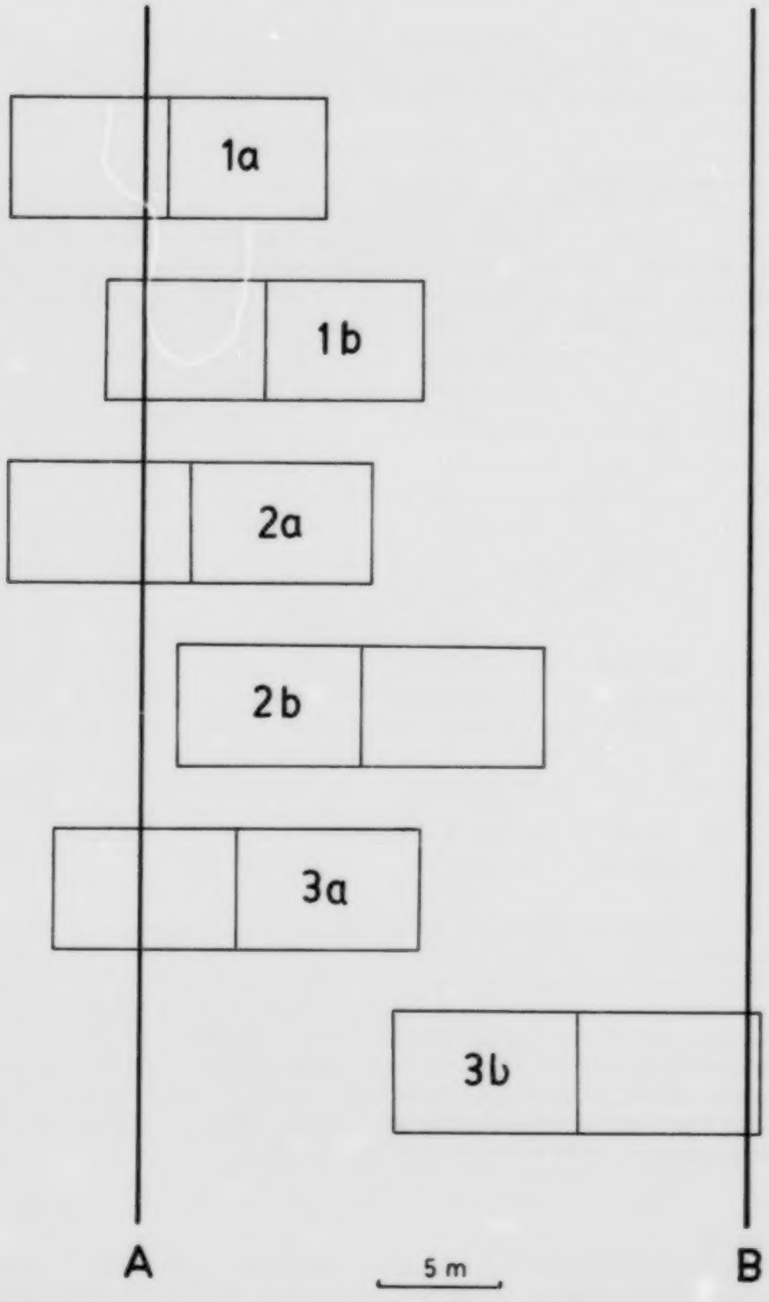


Figure 6. Swath position in relation to crosswind release line (A) and line 25 m downwind (B) (to scale). Labels 1, 2 and 3 denote trial numbers, suffixes a and b refer to windspeeds of 1 and 4 m/s.

## SUMMARY AND CONCLUSIONS

Drift trials were carried out with three rotary-wing ROUNDUP use-strategies employing the MICROFOIL BOOM, Thru Valve Boom, and D8-46 hydraulic nozzle, under meteorological conditions chosen to maximize small drop drift and off-target deposit on downwind water surfaces. Airborne herbicide and off-target deposits on imitation water and foliar surfaces were measured up to 200 m downwind. In general the least and greatest airborne glyphosate concentrations and off-target deposits resulted from the microfoil and D8-46 applications respectively, in accordance with the volume proportions of the spray cloud represented by drops with diameters less than 100 $\mu$m. Estimates were made of the buffer widths required to prevent significant direct toxicological effects on salmon, rainbow trout and aquatic invertebrates from 100 ha applications with the use-strategies tested, using a mathematical model based on the off-target deposit measurements and published toxicological data for fish and aquatic invertebrates. For the MICROFOIL BOOM and Thru Valve Boom use-strategies a buffer width of 25 m from the closest swath will limit ROUNDUP concentrations to less than 1 mg/L, and prevent significant direct toxicological effects from either small or large drop drift. For the D8-46 hydraulic nozzle use-strategy tested a 30 m buffer is needed to prevent swath displacement resulting in the possibility of significant toxicological effects.

## ACKNOWLEDGMENTS

The authors thank the British Columbia Ministry of Forests and Monsanto Canada Inc. for their financial support, and Ron Rowe, Brent Birkedal, Wayne Enlow, David Gubbels, Jim Beveridge and Bozena Staznik for technical assistance during the spray cloud dispersal experiment.

## REFERENCES

Atkinson, B.W. 1981. Meso-scale atmospheric circulations. Academic Press, London, England.

Beveridge, W.J. and N. Payne. 1986. A light-weight mast for use in meteorological or spray drift studies. Forest Pest Management Institute, Canadian Forestry Service, Technical Note Number 5.

Cowell, J.E., J.L. Kunstman, P.J. Nord, J.R. Steinmetz and G.R. Wilson. 1986. Validation of an analytical residue method for analysis of glyphosate and metabolite: an interlaboratory study. J. Agric. Food Chem. 34:955-960.

Crabbe, R.S., L. Elias and S.J. Davie. 1983. Field study of the effect of atmospheric stability on target deposition and effective swath width for aerial forest sprays in New Brunswick. Part II. LTR-UA-65, NAE, NRC, Canada.

Crabbe, R.S. and M. McCooeye. 1985. Effect of atmospheric stability and windspeed on wind drift in aerial forest spray trials, neutral to unstable conditions. LTR-UA-82, NAE, NRC, Canada.

Crosby, D.G. and R.K. Tucker. 1966. Toxicity of aquatic herbicides to *Daphnia magna*. Science. 154:289-290.

Davis, R.E. and J.W. Kelly. 1967. Elementary plane surveying. 4th ed. McGraw Hill Book Company, New York, USA.

Folmar, L.C., H.O. Sanders and A.M. Julin. 1979. Toxicity of the herbicide glyphosate and several of its formulations to fish and aquatic invertebrates. Arch. Environ. Contam. Toxicol. 8:269-278.

Green, H.L. and W.R. Lane. 1964. Particulate clouds: dusts, smokes & mists. E. & F.N. Spon Ltd., London, England.

Hildebrand, L.D., D.S. Sullivan and T.P. Sullivan. 1980. Effects of ROUNDUP on populations of *Daphnia magna* in a forest pond. Bull. Environ. Contam. Toxicol. 25:353-357.

Hildebrand, L.D., D.S. Sullivan and T.P. Sullivan. 1982. Experimental studies of rainbow trout populations exposed to field applications of ROUNDUP herbicide. Arch. Environ. Contam. Toxicol. 11:93-98.

Hinds, W.C. 1982. Aerosol technology: properties, behavior and measurement of airborne particles. John Wiley and Sons, New York, USA.

Joyce, R.J., G.W. Schaefer and K. Allsopp. 1981. Distribution of spray and assessment of larval mortality at Annabaglish. p. 15-46 In Aerial application of insecticide against Pine Beauty moth. A. Holden & D. Bevan (eds.). Forestry Commission, UK.

Matthews, G.A. 1979. Pesticide application methods. Longman, London, England.

May, K.R. and R. Clifford. 1967. The impaction of aerosol particles on cylinders, spheres, ribbons and discs. Ann. Occupational Hyg. 10:83-95.

May, K.R., N.P. Pomeroy and S.D. Hibbs. 1976. Sampling techniques for large windborne particles. J. Aerosol Sci. 7:53-62.

Monsanto. 1983. Analytical methods for the determination of glyphosate and AMPA. Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO.

Monsanto. 1986a. Seawater challenge testing of coho salmon smolts following ROUNDUP herbicide exposure. EV-85-045. Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO, 63167.

Monsanto. 1986b. Acute toxicity of ROUNDUP herbicide to chinook salmon. EV-85-046. Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167.

Monsanto. 1986c. Acute toxicity of ROUNDUP herbicide to coho salmon. EV-85-047. Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167.

Monsanto. 1986d. Acute toxicity of ROUNDUP herbicide to rainbow trout. EV-85-048. Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167.

Neiburger, M., J.G. Edinger and W.D. Bonner. 1973. Understanding our atmospheric environment. W.H. Freeman and Co., San Francisco.

Oliver, H.R. 1971. Wind profiles in and above a forest canopy. Q.J.R. Meteorol. Soc. 97:548-553.

Oliver, H.R. 1975. Ventilation in a forest. Agric. Meteorol. 14:347-355.

Pasquill, F. 1974. Atmospheric diffusion: the dispersion of windborne material from industrial and other sources. 2nd ed. Ellis Horwood Ltd., Chichester, England.

Payne, N. 1983. A quantification of turbulent dispersal and deposition of coarse aerosol droplets over a wheat field. PhD Thesis. Cranfield Institute of Technology. Cranfield. Bedfordshire, MK43 OAL, England.

Payne N., B. Helson, K. Sundaram, P. Kingsbury, R. Fleming and P. de Groot. 1986. Estimating the buffer required around water during permethrin applications. Canadian Forestry Service, Forest Pest Management Institute, Sault Ste. Marie, Ont., Inf. Rep. FPM-X-70.

Payne, N.J., B.V. Helson, K.M. Sundaram and R. Fleming. 1988. Estimating buffer zone widths for pesticide applications. Pestic. Sci. 24:147-161.

Riddick, J.A. and W.B. Bunger. 1970. Techniques of chemistry, volume 2: organic solvents: physical properties and methods of purification. 3rd ed. Wiley Interscience, New York, U.S.A.

Rogers, R.R. 1979. A short course in cloud physics. 2nd ed. Pergamon Press Ltd., Oxford, England.

Scorer, R.S. 1978. Environmental aerodynamics. Ellis Horwood Ltd., Chichester, England.

Sutton, O.G. 1953. Micrometeorology: a study of the physical processes of the lower layers of the earth's atmosphere. McGraw-Hill Book Company Inc., New York, NY.

Thom, A.S. 1975. Momentum, mass and heat exchange of plant communities. p. 57-109 In Vegetation and the atmosphere, volume 1, Principles. J. Monteith (ed.). Academic Press, London, England.

Tooby, T.E. 1985. Fate and biological consequences of glyphosate in the aquatic environment. p. 206-217 In The herbicide glyphosate E. Grossbard and D. Atkinson (eds.). Butterworths, London, England.

van Vliet, M.W., G.W. Henderson and J.C. Picot. 1988. Spectrum characterizations for herbicide atomizers. PRUF report for contracts DSS #23ST. KH 411-4-0015 & #02SE. 01 K38-6.0020. Department of Chemical Engineering, University of New Brunswick.

WSSA (Weed Science Society of America). 1983. Herbicide Handbook. Champaign, Ill.

Yates, W.E., R.E. Cowden and N.B. Akesson. 1985. Atomization of herbicide simulants with hollow cone and raindrop nozzles. FPM 85-1. USDA, Forest Service, Forest Pest Management. Davis, CA 95616.

# DEVELOPMENT OF NON-COMMERCIAL VEGETATION FOLLOWING CLEARCUTTING AND CLEARCUTTING-PLUS-SLASHBURNING, AND SOME BIOGEOCHEMICAL EFFECTS OF HERBICIDAL CONTROL OF THIS VEGETATION

J.P. Kimmins, K.M. Tsze and R.E. Bigley
Department of Forest Sciences
Faculty of Forestry
University of British Columbia
Vancouver, B.C.
V6T 1W5

## ABSTRACT

The development of aboveground biomass of herbs, shrubs and non-commercial deciduous trees was monitored following clearcutting and clearcutting-plus-slashburning in low elevation coastal forests in British Columbia. After eight years, 21 t ha$^{-1}$ of aboveground non-crop vegetation biomass had accumulated on the clearcut site [2.5 t ha$^{-1}$ of herbs, 3.6 t ha$^{-1}$ of shrubs, and 15.1 t ha$^{-1}$ of deciduous trees (mostly red alder)], in comparison to 3.9 t ha$^{-1}$ on the slashburned site [2.6 t ha$^{-1}$ of herbs, 0.8 t ha$^{-1}$ of shrubs, and 0.5 t ha$^{-1}$ of deciduous trees (mostly willow and cottonwood)]. The unburned clearcut area was then sprayed with glyphosate (nine years after cutting). One year following the spray, live aboveground biomass had been reduced to about 2.6 t ha$^{-1}$. This had increased to about 3.5 t ha$^{-1}$ (2.9 t ha$^{-1}$ of shrubs and 0.5 t ha$^{-1}$ of herbs) by three years post-spray (year 12 of the study). In comparison, the slashburned site had an aboveground non-crop biomass of 4.5 t ha$^{-1}$ in the 12th year (3.0 t ha$^{-1}$ of herbs, 1.5 t ha$^{-1}$ of shrubs). Unfortunately, some of the deciduous trees on the slashburned site were manually removed by mistake ten years after the start of the study. No estimate of what their biomass would have been in year 12 is available.

The herbicide treatment had a significant effect on the nitrogen budget of the site. Nitrate concentrations in soil solution were increased about 2.8 times (to a peak concentration of 7.8 mg L$^{-1}$ of $NO_3$), while streamwater concentrations increased 7 times to a peak value of 2 mg L$^{-1}$. A preliminary and incomplete nitrogen budget suggests that somewhere between 80 and 150 kg ha$^{-1}$ of nitrogen (depending upon what assumptions are made) may have been lost in solution in the three years following the herbicide treatment. This compares with an estimated output in logs at the time of harvest of 234 kg ha$^{-1}$ and an estimated input by red alder prior to the herbicide spray of 194 kg ha$^{-1}$. The estimated overall nitrogen balance for 1973-1984 on the herbicide-treated area was -93 to -163 kg ha$^{-1}$ (depending on assumptions). This compares with a nitrogen balance for the slashburned area of -1260 kg ha$^{-1}$ (982 kg ha$^{-1}$ lost in the fire, and 308 kg ha$^{-1}$ lost in harvested materials).

It is concluded that the herbicide treatment caused a significant loss of nitrogen from the ecosystem, but that this was approximately balanced by the symbiotic nitrogen fixation prior to the spray. It is anticipated that the herbicide-related loss would in any case be more than compensated for by precipitation and fixation inputs of nitrogen over a 60-year rotation. The slashburn-related loss of nitrogen was much greater than the herbicide-related loss, and it is doubtful if the loss would be compensated for by natural inputs over a 60-year rotation. It would appear that nitrogen fertilization will be necessary on the slashburned watershed if growth is to be maintained at the same level as that expected on the herbicide-treated area. Where herbicides

are used to kill nitrogen-fixing species, the most dramatic ecological impact of the spray in terms of site biogeochemistry may be the cessation of the nitrogen inputs by symbiotic fixation.

## INTRODUCTION

Hydrological and ecological studies of the devegetation of an eastern deciduous hardwood forest watershed at Hubbard Brook, New Hampshire, in the 1960s and 1970s (Bormann et al. 1968; Likens et al. 1970) led to concerns about the effects of herbicides on streamwater chemistry and on the biogeochemical integrity of ecosystems. Several studies since than have confirmed that herbicide treatments can cause significant increases in the leakage of nitrogen and other nutrients from ecosystems (Johnson and Swank 1973; Sollins et al. 1981; Edwards and Ross-Todd 1979; Miller and Newton 1983; Davis 1984, 1987; Dyck et al. 1983; Vitousek and Matson 1985; Neary et al. 1986). Herbicides are not the only site treatments that can result in nutrient loss, however. Slashburning, which can be used as an alternative to herbicidal control of non-commercial plant competition prior to planting tree crops, can also cause substantial losses of site nutrient capital (e.g., Harwood and Jackson 1973; Flinn et al. 1979; Nissley et al. 1980; Feller 1982; Feller and Kimmins 1984). The study reported in this paper was part of a research project initiated in 1971 to quantify the nutrient losses and regrowth of minor vegetation associated with clearcut harvesting, followed after one year by broadcast slashburning or after ten years by herbicidal control of competing vegetation. The paper describes the development of non-crop vegetation following the treatments, and some biogeochemical effects of herbicidal control of this vegetation. The development of crop tree biomass over this time was not studied.

### Study Location, Site Description and Experimental Treatments

The study was conducted in two small (less than 30 ha) first order watersheds at 145 to 310 m elevation at the University of B.C. Research Forest at Haney, 60 km east of Vancouver, B.C. The watersheds are located in the dry subzone of the Coastal Western Hemlock biogeochemical zone, (Köppen climate: Cfb) (Krajina 1969) on a gentle southerly slope at an elevation of about 200 m. The soils are generally humo-ferric podzols (Canadian Soil Survey Committee 1978) developed in sandy-loam to loamy-sand with an average soil cation exchange capacity of 31 meq/100 g. The area has a marine, warm-temperate, rainy climate with an annual precipitation of 220-270 cm. Prior to clearcutting, the watersheds carried an approximately 100-year-old coniferous forest dominated by western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], Douglas-fir [*Psudotsuga menziesii* (Mirb.) Franco] and western red cedar (*Thuja plicata* Donn); the stand originated from a wildfire in 1868.

Approximately 15 ha was clearcut and highlead logged in the fall/winter of 1973/74 and spring of 1974 in each of two watersheds equipped with sharp-crested V-notch weirs. Water flow and stream chemistry had been monitored weekly for two years prior to the logging. Following clearcutting, one of the clearcuts (East Creek) was broadcast slashburned in the late summer of 1974. The other clearcut (Marc Creek) was left unburned. Both clearcuts were planted with Douglas-fir seedlings in 1975, although much of the Marc Creek clearcut was not planted because of heavy slash and the rapid development of shrubs [dominated by salmonberry (*Rubus spectabilis* Pursh.)]. A significant amount of natural regeneration of the above three coniferous species developed on the Marc Creek clearcut over the 12 years of study. There was little such invasion on the East Creek clearcut.

The regrowth of minor vegetation was monitored on both clearcuts until 1982, when the Marc Creek clearcut was sprayed (in June) with 3 kg a.i. $ha^{-1}$ of glyphosate (ROUNDUP). Aboveground biomass of herbs and shrubs was monitored five times between clearcutting (in 1973/74) and the 1982 herbicide treatment by clipping 54 1-$m^2$ plots distributed in a stratified-random sampling scheme on each clearcut. Deciduous tree growth was also monitored by means of these clip plots until 1981. After 1981, deciduous tree biomass was estimated using biomass regression equations obtained from the literature (Gholz et al. 1979) in conjunction with data on deciduous tree diameters from eighteen 3 m radius circular plots distributed at random along the existing sampling transects. Macronutrient analyses were conducted on all plant samples, and a variety of other biogeochemical studies were conducted (details in Kimmins 1987). Streamflow and streamwater chemistry were analysed throughout most of the 13 years of the study. Lack of funding prevented the monitoring of the growth of the planted Douglas-fir and natural regeneration of conifers on the sites.

## RESULTS

### Losses of Nutrients by Log Removal and Slashburning

Losses of nutrients (kg $ha^{-1}$) from the two clearcuts in harvested logs, by streamwater export (dissolved nutrients leaving the watershed over the V-notch weirs), and by gassification and flyash during burning from the slashburned East Creek clearcut are shown in Table 1. With the exception of magnesium, stream exports over the weirs were relatively small in comparison to other loss pathways, although the methodology used does not give a reliable measure of losses of nutrients from the watershed. Export of nutrients in particulate matter during storm events was not monitored, dissolved organic nitrogen and organic phosphorous were not measured, and there was no accounting for long-term immobilization of nutrients in stream sediments. Nor was there any quantification of denitrification losses either in the stream or in the clearcuts. Recent evidence (Martin 1985) suggests that denitrification may sometimes be a major post-clearcutting N loss from the forest floor in the humid maritime climates of the British Columbia coast in the absence of slashburning. Denitrification may result in the loss from the stream of much of the nitrogen leached from the land into the stream (M.C. Feller, personal communication). As a result, streamwater analysis may not be an adequate method by which to estimate leaching losses from the land.

Table 1. Estimated nutrient losses (kg $ha^{-1}$) from Marc Creek (MC) and East Creek (EC) clearcuts at the Haney Research Forest near Vancouver, B.C. during 1973-75 (from Feller and Kimmins 1984)

| | N | | P | | K | | Ca | | Mg | |
|---|---|---|---|---|---|---|---|---|---|---|
| | MC | EC | MC | EC | MC | EC | MC | EC | MC | EC |
| Streamwater exports | 11 | 3 | 0 | 0 | 11 | 9 | 44 | 55 | 9 | 10 |
| Harvest removals (in logs) | 234 | 308 | 34 | 50 | 168 | 237 | 260 | 467 | 27 | 38 |
| Atmospheric loss due to slashburning | - | 982 | - | 16 | - | 37 | - | 154 | - | 29 |

Losses of nutrients in harvested materials were somewhat less on the Marc Creek clearcut than on the East Creek clearcut, the observed differences being attributed to differences in tree species composition and the volume of logs removed. Harvest removals constituted a much greater loss than estimated streamwater exports. Although the latter are undoubtedly significant underestimates (as noted above), the true leaching losses from the sites were probably small relative to the harvest removals, with the possible exception of magnesium. Losses of N from the East Creek clearcut during the slashburn were about three times as great as the log exports of N. Losses of the other macronutrients caused by slashburning were much smaller, but they were biologically significant and three or more times greater than the estimated dissolved streamwater losses (but remember that the latter estimates are probably too low).

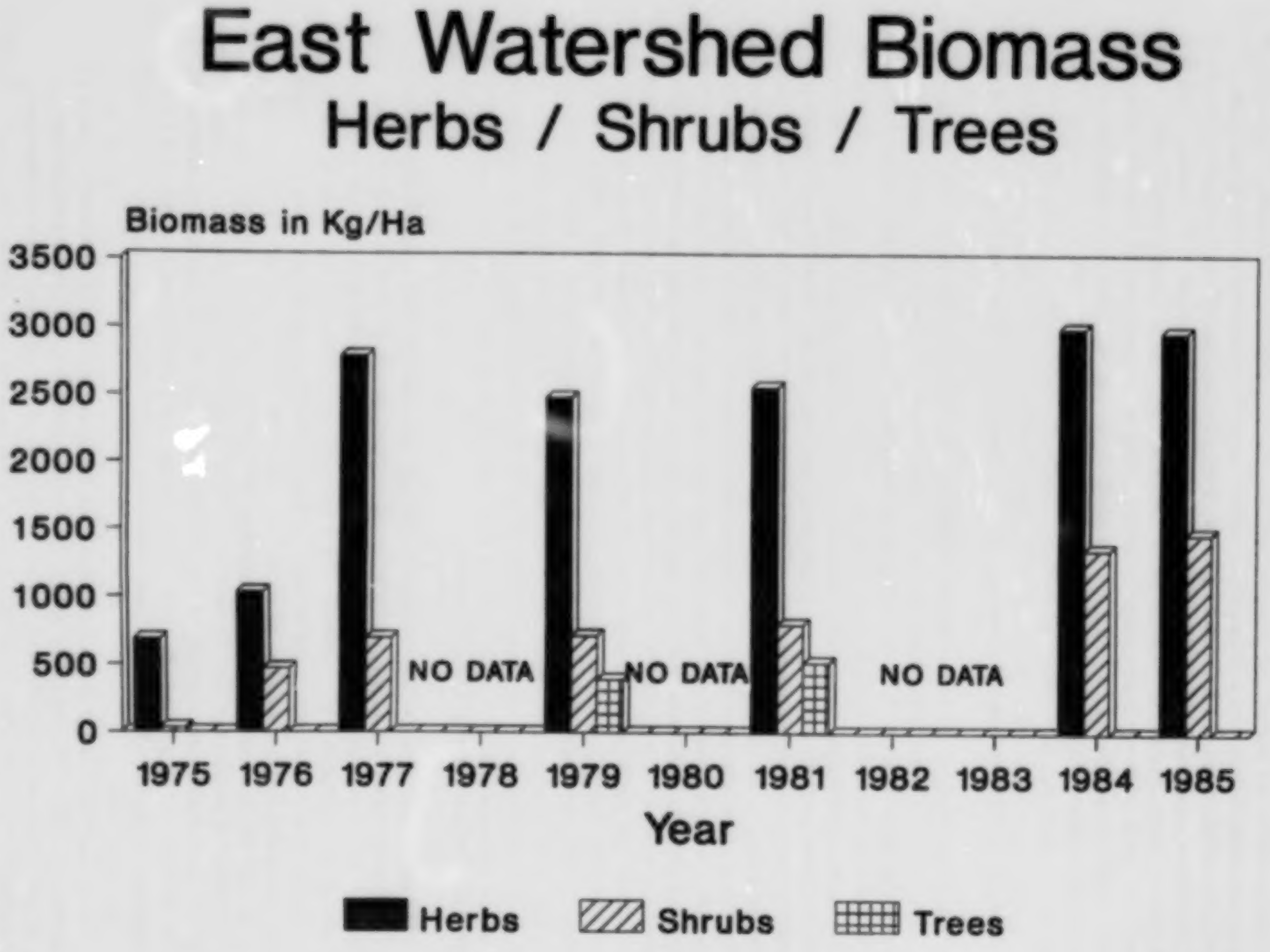
### Post-clearcutting Development of Aboveground Non-commercial Plant Biomass

The development of herb, shrub and deciduous tree biomass on the East Creek and Marc Creek clearcuts between 1975 and 1985 are shown in Figures 1a and 1b. On both clearcuts, herbs developed a biomass of about 2.5 t $ha^{-1}$ by 1979 (six years after logging on the Marc Creek clearcut and five years after slashburning on the East Creek clearcut). Herb biomass continued to increase on the slashburned clearcut, to about 3 t $ha^{-1}$ by 10 years post-burning. The slower development and lower final aboveground biomass of herbs on the unburned Marc Creek clearcut was the result of the greater development of shrub and deciduous tree biomass on the unburned clearcut than on the burned clearcut. Shrubs achieved an aboveground biomass of about 3.8 t $ha^{-1}$ on the unburned clearcut four years after clearcutting, compared with 0.7 t $ha^{-1}$ on the burned clearcut. Similarly, aboveground biomass of deciduous trees had reached an estimated 10.3 t $ha^{-1}$ by 1979 on the unburned clearcut, in comparison with 0.4 t $ha^{-1}$ on the burned watershed. These values increased to 15 t $ha^{-1}$ and 0.5 t $ha^{-1}$, respectively, by 1981, the year before the Marc Creek clearcut was treated with herbicides. Unfortunately, some of the developing deciduous trees [mostly willows (*Salix* spp. L.) and cottonwoods (*Populus trichocarpa* Torr. and Gray)] were manually removed from the burned clearcut by mistake in 1983, so the comparisons are only valid until 1981.

### Successional Patterns on the Two Clearcuts

The early succession on the burned clearcut was dominated by *Polytrichum juniperinum* Hedw., a pioneer moss that commonly forms a dense mat a few years after burning in coastal forest ecosystems. This moss layer appears to inhibit the invasion of vascular plant species other than those that spread vegetatively by rhizomes. As a result of the *Polytrichum* layer, the vegetation on the burned clearcut was dominated initially by fireweed (*Epilobium angustifolium* L.), which reached a peak aboveground biomass of about 1.2 t $ha^{-1}$ by 1984, three years after burning. Thereafter, the herbaceous layer was dominated by bracken fern [*Pterdium equilinum* (L.) Kuhn], which increased to an aboveground biomass of 2.7 t $ha^{-1}$ by 1984, ten years after burning. These two species accounted for the majority of the herb biomass, which remained greater than the shrub biomass until the end of the study in 1985, when shrubs had a total biomass of only 1.5 t $ha^{-1}$ in comparison to the herb biomass of about 3.0 t $ha^{-1}$.

The combination of the *Polytrichum* layer and the dense community of fireweed and bracken fern appeared to effectively prevent or greatly inhibit the invasion of shrubs and deciduous trees, in spite of abundant nearby seed sources. Shrubs that were present prior to clearcutting resprouted from rootstocks after burning, but the aboveground biomass development was much slower



East Watershed Biomass
Herbs / Shrubs / Trees

Figure 1a.

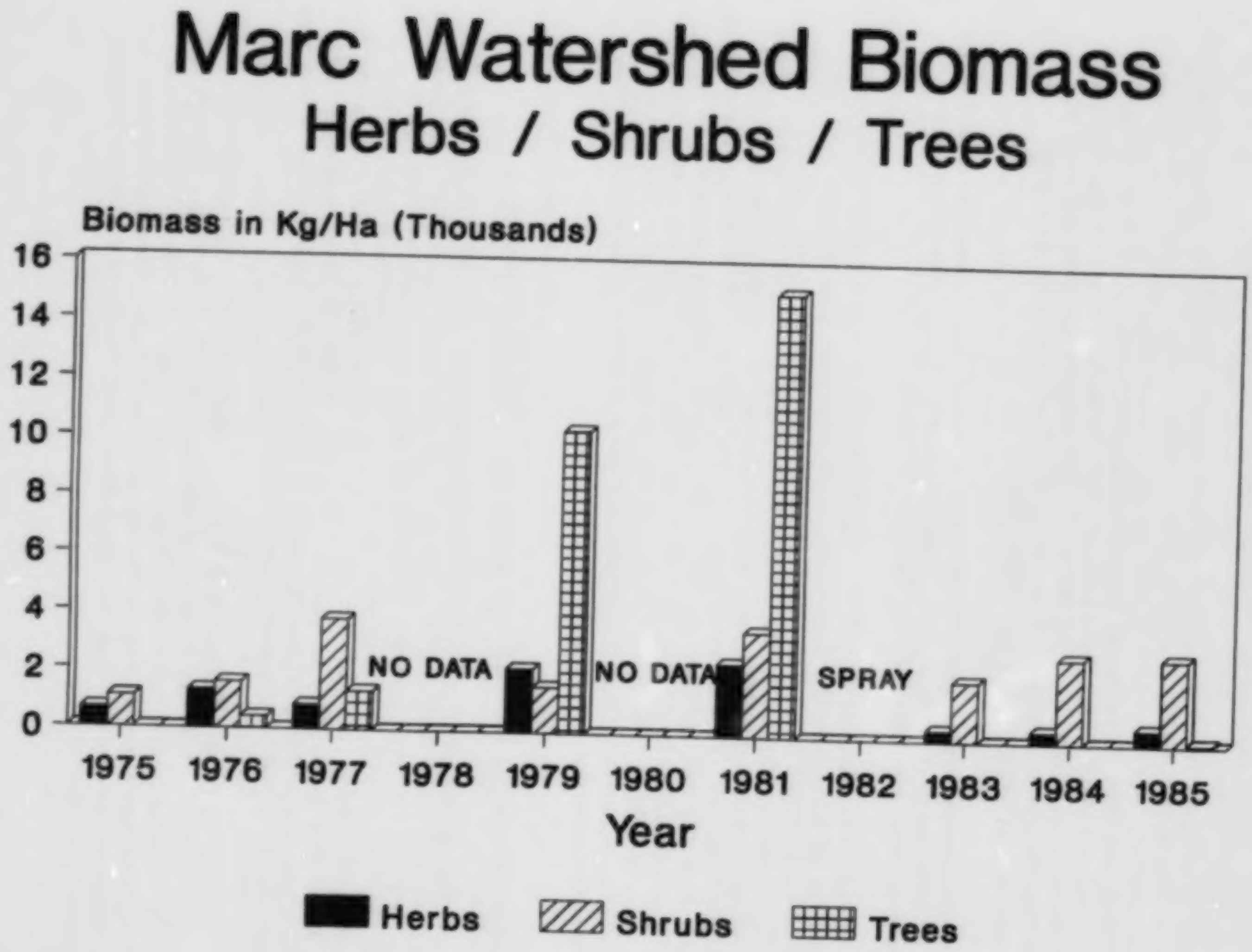

Marc Watershed Biomass
Herbs / Shrubs / Trees
Biomass in Kg/Ha (Thousands)
16
14
12
10
8
6
4
2
0
NO DATA
NO DATA
SPRAY
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
Year
Herbs
Shrubs
Trees

Figure 1b.

(due primarily to competition for light) than on the unburned clearcut: 3.8 t $ha^{-1}$ by 1977 on the unburned area vs about 0.7 t $ha^{-1}$ on the burned area. The shrub species composition was not greatly different between two clearcuts. The major difference was the biomass.

On the unburned Marc Creek clearcut, fireweed achieved an aboveground biomass of about 0.5 t $ha^{-1}$ in 1976, three years after clearcutting (compared with 1.2 t $ha^{-1}$ on the burned site), and then declined to about 0.4 t $ha^{-1}$ in 1981, just before the herbicide treatment. In contrast, aboveground bracken fern biomass increased throughout the study, to a level of 1.0 t $ha^{-1}$ in 1981 (compared with 2.0 t $ha^{-1}$ on the burned site). The decline in fireweed is attributed to both increased competition from bracken and shrubs, and also to the end of the post-clearcutting "assart" flush of nutrient availability. These two species accounted for the majority of the herbaceous biomass on both burned and unburned sites.

Shrub biomass increased rapidly on the unburned clearcut, dense communities of salmonberry being the major feature of the shrub layer. Dense patches of salal (*Gaultheria shallon* Pursh.), thimbleberry (*Rubus parviflorus* Nutt.) and *Vaccinium* spp. also developed.

In addition to differences in shrub development, succession on the two clearcuts was differentiated by the development of a closed-canopy tree layer on much of the unburned area. This tree layer was dominated by red alder (*Alnus rubra* Borg.), but there were increasing contributions from big leaf and vine maples (*Acer macrophyllum* Pursh. and *A. circinatum* Pursh.) by 1981. These latter two species were scattered irregularly across the area and the sampling scheme was not able to document their biomass development accurately. There were also minor occurrences of cottonwood (*Populus trichocarpa* Torr. and Gray) and willows (*Salix* spp. L.). Deciduous hardwoods on the burned area were much less abundant and were mostly willows, cottonwoods and western paper birch (*Betula papyrifera* Marsh.). By the end of the study, the growth of coniferous tree species was beginning to influence the biomass of both herbs and shrubs, especially on the burned watershed, but the coniferous biomass was not quantified.

### Impact of the Herbicide Treatment on Plant Biomass and Species Composition

In the year after the glyphosate spray, midsummer aboveground live plant biomass on the Marc Creek clearcut was reduced to about 2.6 t ha , slightly higher than two years after clearcutting (1.7 t $ha^{-1}$). Three years after the spray, the aboveground biomass had recovered to about 3.5 t $ha^{-1}$. Shrubs were more important and herbs less important three years after the herbicide treatment than three years after the clearcut, and the species composition of the shrubs had changed from dominance by salmonberry to dominance by salal and the creeping shrub, *Rubus ursinus* (Cham. and Schl.). Red alder was eliminated, and vine maple, cottonwoods and willows were greatly reduced. Bigleaf maple was not greatly affected.

Although the conifers suffered extensive leader dieback and death of the 1982 new needle and branch growth, by 1985 they had almost all recovered, established new leaders (although there were a lot of double leaders), and appeared to be extremely healthy. In 1985, the needle size of the Douglas-fir trees on the herbicide-treated clearcut was much larger. There appeared to be more foliage per tree, and the foliage was a much darker green than that of the Douglas-fir on the slashburned East Creek clearcut.

## Nutritional Content of the Vegetation

In 1981, eight years after clearcutting, the aboveground non-commercial vegetation on the unburned Marc Creek clearcut contained the following quantities of macronutrients (kg ha $^{-1}$): N-222; P-32; K-146; Ca-115; and Mg-29. These values compare with the following losses of these elements (kg ha $^{-1}$) in harvested materials in 1973: N-234; P-34; K-168; Ca-260; and Mg-27. In the same year, the non-commercial vegetation on the burned clearcut contained the following quantities of macronutrients (kg ha$^{-1}$ ): N-60; P-10; K-43; Ca-21; and Mg-7. Clearly, the non-commercial vegetation was holding significantly more nutrients on the unburned site than on the burned site. Following the herbicide treatment, the nutrient content (kg ha$^{-1}$ ) of the non-commercial vegetation on the unburned clearcut was reduced to N-42; P-4; K-22; Ca-21; and Mg-5. The difference (N-180; P-28; K-124; Ca-94; and Mg-24 kg ha$^{-1}$ ) in content represents nutrients available to the developing conifer crop via organic matter decomposition and mineralization, less any nutrients lost by leaching (or, for N, denitrification).

## Nitrogen Losses from the Herbicide-treated Site Following Treatment

Concentrations of nitrate in soil solution were 2.8x higher during the 12 month period September 1982 - September 1983 (following the herbicide treatment) compared with the previous 10 months (November 1982 - August 1982 - essentially pre-herbicide treatment values). This compares with a 7x increase in streamwater nitrate concentrations for the same periods. However, mean and peak lysimeter nitrate concentrations (7.8 and 10.5 mg L$^{-1}$ , respectively were much higher than mean and peak streamwater concentrations (2.8 and 4.6 mg L$^{-1}$ respectively). The lower values for streamwater are believed to reflect in-stream processing of nitrogen. This removal of nutrients from solution means that streamwater solution exports of nitrogen are probably a poor index of the extent of nitrogen losses from the site. Feller (in press) reports details of streamwater chemistry before and five years following the herbicide treatment.

## Estimated Nitrogen Budgets

Table 2 presents an estimated nitrogen budget for the two clearcuts. Because of funding limitations and technical difficulties, the data necessary to produce a detailed budget were not collected. In particular, the lack of reliable data on actual solution losses from land to streams, on denitrification losses (on land and in the stream), and on in-stream processing of nitrogen prevent more than very tentative conclusions from being reached. From work on Vancouver Island (Martin 1985), it is believed that significant denitrification losses of nitrogen may have occurred on the unburned site both after logging and after the herbicide treatment, times when there was an abundance of nitrate-nitrogen. However, based on the budget in Table 2, it would appear that permitting the site to be occupied by alder for several years followed by herbicidal removal resulted in a significantly improved site nitrogen balance in comparison to slashburning; a not unexpected result. This conclusion is supported by observations and preliminary data on the relative growth, foliage colour and needle dimensions of Douglas-fir trees on the two clearcuts. All of these parameters had more desirable values on the Marc clearcut than on the East clearcut.

Table 2. Preliminary nitrogen budget for the Marc Creek and East Creek clearcuts in the 1973 to 1985 period.

| Inputs | MC | EC |
|---|---|---|
| Precipitation (measured) | 48 | 48 |
| Symbiotic fixation (estimated) | 194 | Negligible |
| Non-symbiotic fixation | Not measured | Not measured |
| TOTAL INPUTS | 242 | 48 |
| Outputs | | |
| Streamwater exports 1973-75 (measured) | 11 | 3 |
| Streamwater exports 1975-82[1] (measured) | 10 | 8 |
| Streamwater exports 1982-85[1] (estimated) | 80-150 depending on assumptions | 4[2] |
| Denitrification losses[2] | Not measured | Not measured |
| Harvested material (measured) | 234 | 308 |
| Fire (measured) | - | 982 |
| TOTAL OUTPUTS | 335 to 405 | 1305 |
| NET BALANCE | -93 to -163 | -1257 |

---

[1] Data courtesy of M.C. Feller.

[2] Feller, M.C. (in press).

[3] Potentially much larger on the unburned than on the burned clearcut.

Although the overall nitrogen budget was more positive for the Marc clearcut than for the East clearcut, Feller (in press) reports that the herbicide treatment resulted in a loss of about 40 kg ha$^{-1}$ nitrate-nitrogen in streamwater from the Marc clearcut over the five post-treatment water years, compared with a loss of 7 kg ha$^{-1}$ in the five years after clearcutting, and a loss of 20 kg ha$^{-1}$ in the five years after clearcutting and slashburning on the East clearcut. These results are consistent with Neary et al. (1986). Based on the measured average annual precipitation and average lysimeter sample concentrations of nitrate-nitrogen, it is estimated that about that about 40 kg ha $^{-1}$ of nitrate-nitrogen was leached to below the rooting zone in the year following the spray (about 11 times the precipitation input for that period). The coincidence between the streamwater export values and the lysimeter values suggests that there was little loss of nitrate within the stream environment. However, this is in conflict with in-stream denitrification experiments (Feller, personal communication) and with the results of stream enrichment experiments (Kimmins 1987). The discrepancy between these different experimental approaches cannot be explained on the basis of the data presently available.

Ammonium-nitrogen concentrations in the lysimeter samples and streamwater samples were very low, and losses of ammonium-nitrogen are assumed to have been very low. Organic-nitrogen was not measured in lysimeter samples, but Martin (1985) reported that on the clearcuts he studied in coastal British Columbia, organic-nitrogen greatly exceeded nitrate-nitrogen in his lysimeter samples; 60-77% of the nitrogen in his lysimeter samples was in organic form. Organic-nitrogen concentrations in streamwater samples in this study were slightly higher than nitrate-nitrogen concentrations and exhibited a similar treatment response (Feller, personal communication). If it is assumed that the ratio of nitrate-nitrogen/organic-nitrogen in the lysimeter samples was the same as in streamwater, it is possible that 80-90 kg N ha $^{-1}$ may have been lost from the Marc clearcut in drainage water in the year following the herbicide treatment. If the ratio observed in Martin's (1985) study is used, the value might have been as high as 150 kg N ha $^{-1}$

Using the available data and estimates of nitrogen inputs and outputs over the 1973-1985 period, it is estimated that the East clearcut had a net loss of 1257 kg N ha $^{-1}$, out of a pre-clearcut soil reserve of about 6000 kg N ha $^{-1}$ (Feller and Kimmins 1984). The Marc clearcut probably had a net loss of between about 90 and about 160 kg N ha $^{-1}$. In terms of total site N, neither of these losses is dramatic, but the loss on the East clearcut probably represents a significant proportion of the readily mineralizable organic-nitrogen reserves, and the loss is unlikely to be replaced by precipitation inputs over a 60-year rotation. Nitrogen fertilization will probably be necessary if tree growth on the East clearcut is to be maintained at the same level as that on the Marc watershed.

## CONCLUSIONS

Many of the very productive lower-slope forests of low elevation coastal British Columbia may well owe their high productivity to a natural succession following past natural disturbance (fire, windblow) that included occupancy of the site by red alder for periods of up to 80 years. Intensive forest management in this area has had as its objective the elimination of this alder seral stage. Basic ecological principles would suggest, and the data from this study support the idea, that elimination of this seral stage may result on some sites in reduced productivity over the next rotation unless nitrogen fertilizers are used, especially if sites are prepared for planting by a hot slashburn. Research is needed to investigate various management strategies in which some degree of site occupancy by red alder is favored over some portion of the rotation. As the commercial acceptability of red alder increases, the alder "nurse crop" may be removed as an economic crop. Until then, manual or chemical killing of the alder will be necessary at the time when the benefits of nitrogen-fixation become outweighed by the negative effects of light competition. From the data produced by this study, it does not appear that chemical removal of the alder is unacceptable from a biogeochemical point of view, and other studies (Bigley 1988) suggest that there may sometimes be some ecophysiological advantages to releasing Douglas-fir from alder competition using herbicides rather than by manual removal.

## ACKNOWLEDGMENTS

The technical assistance in this project of Dr. M.C. Feller (streamflow and streamwater chemistry, and estimates of harvest and slashburning-related nutrient losses), Richard Bigley and Min Tsze (field sampling and laboratory analyses of plant biomass), several summer technicians, and Patsy Quay (typing) are gratefully acknowledged. The project was supported by grants and research contracts from NSERC, Canadian Forestry Service (ENFOR and PRUF grants), and the B.C. Ministry of Forests. This financial support is deeply appreciated. Much of the background work for this project was conducted by Dr. Feller as part of his Ph.D. thesis research, University of British Columbia, and subsequently, as part of his work whilst an NSERC Post-Doctoral Fellow and a University Research Fellow in the Forest Ecology Laboratory at U.B.C. We are very grateful to Linda Kachur for the typing of the paper.

## LITERATURE CITED

Bigley, R.E. 1988. Ecological physiology of conifer seedling and sapling suppression by, and release from, competing vegetation. Ph.D. Thesis. Univ. of B.C., Vancouver. 133 p.

Bormann, F.H., G.E. Likens, D.W. Fisher and R.S. Pierce. 1968. Nutrient loss accelerated by clearcutting of a forest ecosystem. BioScience 19:600-610.

Canada Soil Survey Committee, Subcommittee on Soil Classification. 1978. The Canadian system of soil classification. Can. Dept. Agric. Publ. 1946. Ottawa, Ontario: Supply and Services Canada. 164 p.

Davis, E.A. 1984. Conversion of Arizona chaparral to grass increases water yield and nitrate loss. Water Resour. Res. 20:1643-1649.

Davis, E.A. 1987. Chaparral conversion to increase streamflow in Arizona: Sequential treatments extend duration of nitrate loss to streamwater. Forest Sci. 33:89-103.

Dyck, W.J., J.R. Gosz and P.D. Hodgkins. 1983. Nitrate losses from disturbed ecosystems in New Zealand--a comparative analysis. N.Z. J. For. Sci. 13:14-24.

Edwards, N.T. and B.M. Ross-Todd. 1979. The effects of stem girdling on biogeochemical cycles within a mixed deciduous forest in eastern Tennessee. I. Soil solution chemistry, soil respiration, litterfall and root biomass studies. Oecologia 40:247-237.

Feller, M.C. 1982. The ecological effects of slashburning with particular reference to British Columbia: a literature review. Land Management Report No. 23. ISSN 0702-9861. B.C. Ministry of Forests, Victoria, B.C.

Feller, M.C. 1989. Effects of forest herbicide applications on streamwater chemistry in southwestern British Columbia. Water Resour. Bull. In press.

Feller, M.C., and J.P. Kimmins. 1984. Effects of clearcutting and slashburning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia. Water Resour. Res. 20(1):29-40.

Flinn, D.W., P. Hopmans, P.W. Farrell and J.M. James. 1979. Nutrient loss from the burning of Pinus radiata logging residue. Austr. For. Res. 9:17-23.

Gholz, H.L., C.C. Grier, A.G. Campbell and A.T. Brown. 1979. Equations and their use for estimating biomass and leaf area of Pacific Northwest trees, shrubs and herbs. For. Res. Lab., Sch. For., Oregon State Univ., Corvallis, Oregon. Res. Pap. 41. 37 pp.

Harwood, C.E. and W.D. Jackson. 1975. Atmospheric losses of four plant nutrients during a forest fire. Australian Forestry 38:92-99.

Johnson, P.L. and W.T. Swank. 1973. Studies of cation budgets in the southern Appalachians on four experimental watersheds with contrasting vegetation. Ecol. 54:70-80.

Kimmins, J.P. 1987. Effect of herbicidal reduction of early successional vegetation on the biogeochemistry of a small low elevation watershed in coastal British Columbia. Final, Contract Report. Canadian Forestry Service. PRUF Contract 01SE-5-0020; OS85-0068.

Krajina, V.J. 1969. Ecology of Forest Trees in British Columbia. Ecology of Western North America. Vol. 2, No. 1. Dept. of Botany, Univ. of B.C., Vancouver.

Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher and R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed ecosystem. Ecological Monographs. Vol. 40, pp. 23-47.

Martin, W.L. 1985. Post-clearcutting forest floor nitrate dynamics and regeneration response in the Coastal Western Hemlock wet subzone. Ph.D. Thesis. Faculty of Forestry, Univ. of B.C., Vancouver. 350 pp.

Miller, J.H. and M. Newton. 1983. Nutrient loss from disturbed forest watersheds in Oregon's coast range. Agro-Ecosystems 8:153-167.

Neary, D.G., P.B. Bush and M.A. Grant. 1986. Water quality of ephemeral forest streams after site preparation with the herbicide hexazinone. For. Ecol. & Mgmt. 14:23-40.

Nissley, S.D., R.J. Zasoski and R.E. Martin. 1980. Nutrient changes after prescribed surface burning of Oregon ponderosa pine stands. pp. 214-219. In: Sixth Conference on Fire and Forest Meteorology. Soc. Am. For. and Am. Meterol. Soc.

Sollins, P., K. Cromack Jr., F.M. McCorison, R.H. Waring and R.D. Harr. 1981. Changes in nitrogen cycling at an old-growth Douglas-fir site after disturbance. J. Environ. Qual. 10:37-42.

Vitousek, P.M. and P.A. Matson. 1985. Disturbance, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. Ecology 66:1360-1376.

# EFFECTS OF GLYPHOSATE (ROUNDUP) ON BIOLOGICAL ACTIVITY OF TWO FOREST SOILS

C.M. Preston and J.A. Trofymow
Pacific Forestry Centre
Canadian Forestry Service
506 West Burnside Rd.
Victoria, B.C. V8Z 1M5

## ABSTRACT

The effects of glyphosate (ROUNDUP) on some biological processes were examined in laboratory and field trials. In the laboratory study, forest floor material and mineral soil (0-5 cm depth) from a Douglas-fir site at Shawnigan Lake (Vancouver Island) were incubated with ROUNDUP (10 and 50 $\mu$g a.i./g), with or without 15N-labelled urea (at 200 $\mu$g/g N). No significant effects of ROUNDUP at either level of application were found on carbon dioxide evolution, urea hydrolysis, nitrification, or immobilization of ammonium, for either forest floor or mineral soil layers. In field studies, soil fauna and microflora populations were monitored in surface organic layers prior to and following ROUNDUP application on alder-covered sites at Carnation Creek (Vancouver Island). In a 6-month study, ROUNDUP had no significant long-term effects on populations of soil fauna or microflora. In an intensive 1-month field sampling trial, soil microflora populations in ROUNDUP-treated plots fluctuated, and then returned to control levels.

## INTRODUCTION

When a herbicide is used for vegetation control, incomplete interception by vegetation allows direct contact of the herbicide with the soil. Several studies have been carried out on the impact of glyphosate (or its commercial formulation ROUNDUP, which is a trademark of Monsanto Corp.) on biological activity in soils, and its effects on soil fauna (Eijsackers 1985) and on microflora (Grossbard 1985). The present study investigated the impact of ROUNDUP on two forest soils in laboratory and field studies.

The laboratory study examined the effect of ROUNDUP on microbial activity, as assessed by respiration and nitrogen transformations (hydrolysis of urea, immobilization of ammonium N, and nitrification). The purpose of the field trials was to monitor the dynamics of soil organism populations over a 6-month period in areas sprayed with ROUNDUP under operational conditions. A follow-up experiment monitored the immediate impact of glyphosate for 1 month following application.

## MATERIALS AND METHODS

### Laboratory Study

Forest floor (L-H) and mineral soil (0-5 cm) samples were collected in May 1982 from a 34-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantation near Shawnigan Lake, approximately 50 km northwest of Victoria, British Columbia. The soil is classified as an Orthic Dystric Brunisol, and the thickness of the forest floor averages 3 cm. Some physical and chemical characteristics of the soil samples are listed in Table 1. Details of climate, vegetation and topography of the plantation are reported by Crown and Brett (1975). Immediately after collection, the samples were air-dried at room temperature. Forest floor material was ground with a Wiley mill to pass a 2-mm sieve, and mineral soil was passed through a 2-mm sieve without grinding.

Table 1. Some physical and chemical properties of the Shawnigan Lake soil

| Depth | Bulk Density g/cm | pH | %C | %N | C/N |
|---|---|---|---|---|---|
| L-H (3 cm) | 0.2 | 5.6 | 18.76 | 0.53 | 35 |
| Mineral (0-5 cm) | 1.2 | 5.6 | 2.41 | 0.1 | 24 |

The soil treatments were: (1) urea, (2) ROUNDUP, (3) urea plus ROUNDUP, and (4) untreated control. Glyphosate isopropylamine [(N-phosphonomethyl) glycine] was used as ROUNDUP, 356 g a.i./L from Monsanto Canada Inc. The urea was enriched in 15N at 10.5% above natural abundance.

For the study of $CO_2$ evolution, ROUNDUP and/or urea were applied as solutions to L-H or mineral soil samples in 250-mL beakers, to give equivalent concentrations of 50 μg a.i./g and 200 μg N/g, respectively (air-dry soil basis). Distilled water was added to bring the soil moisture to field capacity (100% v/w for L-H and 30% v/w for mineral soil). Immediately after mixing, a vial containing 5 mL of 0.25 N NaOH was placed in the center of each beaker to absorb $CO_2$. The beakers were covered with parafilm and incubated at 20±1°C. During the first 5 days, the NaOH reservoirs were changed daily and titrated to determine the quantity of $CO_2$ absorbed. Thereafter, until the end of the sixth week, the NaOH reservoirs were changed every 4 days.

For the study of nitrogen transformations, triplicate L-H (100 g) and mineral soil samples (200 g) were weighed into 1-L mason jars. ROUNDUP and/or urea solutions were added to give soil concentrations of 10 and 50 μg a.i./g ROUNDUP and 200 μg N/g, and the soil moisture brought up to field capacity with distilled water. After mixing, samples were covered with perforated parafilm to allow air circulation, weighed, and incubated at 20°C. Subsamples (10 g L-H and 20 g mineral soil) were removed from each mason jar periodically for analysis of total, urea, ammonium, and nitrate N. Sampling was carried out after 2 days, and 1,2,3, and 6 weeks at the 50 μg a.i./g herbicide level, and at 3 and 6 weeks only for the 10 μg a.i./g herbicide level.

For analysis of urea, ammonium and nitrate, soil subsamples were shaken for 30 minutes in a solution of 2.5 N KCl and 2.5 mg/L phenylmercuric acetate (PMA) using a 1:5 ratio of soil to extractant. The samples were centrifuged, and the supernatants filtered through Whatman number 42 filter paper. Soil residues were rinsed twice with 30 mL distilled water to remove residual KCl and PMA, centrifuged, and filtered. The extracts were analysed using a Technicon Autoanalyser. Urea and nitrate were analysed by Technicon industrial methods 600-80A and 487-77A respectively. Due to interference of the soluble organic N in the soil extracts, ammonium was analysed by a modified Technicon industrial method 98-70W (White and Gosz 1981). Results of the urea, ammonium and nitrate analyses are reported as µg N/g of air-dry soil. The soil residues were oven-dried at 70°C, ground and analysed for total N by the semi-micro Kjeldahl method (Pang and McCullough 1985). The distillates from the Kjeldahl digests were acidified, condensed and stored for 15N isotope analysis with a mass spectrometer (MAT GD-150). For carbon dioxide analysis, the NaOH from the trap was transferred to a 50-mL beaker, 4-mL 2N $BaCl_2$ added to precipitate $CO_2$ in NaOH as $BaCO_3$, and the excess NaOH titrated with 0.2 N HCl using an end point of pH 8.0.

## Field Studies

Soil organism populations were monitored on field sampling plots established on spray blocks (sites) 1 and 2 or on adjacent untreated areas of the Carnation Creek herbicide trials. Locations and descriptions of these spray blocks are reported elsewhere in this volume (Reynolds et al. 1989). The sampled areas in both blocks were in the floodplain, and were receiving areas for up-slope drainage. Soils were moderately deep, at least 50-60 cm, with 10- to 35-cm-thick organic layers containing a well-developed humus layer. Soils were gravelly to sandy loam and were classified as a Ferro-humic Podzol. Red alder and salmonberry dominated the site prior to herbicide application.

Two studies were conducted. A long-term 6-month experiment was initiated in August, one month prior to the operational spraying, and lasted through January, with monthly sampling. A short-term 1-month experiment, sampled weekly, was initiated and completed in November. For the long-term trial, samples were taken from three replicate 2 x 2m sampling plots established in each of the spray blocks (treated) and adjacent unsprayed areas (control). For the short-term trial, two separate 5 x 5m sampling plots were established in the control area adjacent to site 1, and one plot was hand sprayed with ROUNDUP at the same rate as the operational application -- 2 kg a.i./ha (0.2 g a.i./$m^2$). This represents approximately 20 µg a.i./g litter given the dry bulk density of the top 5 cm of litter as 0.2 g/cm .

Soil cores (5 cm in diameter) or 30-$cm^2$ blocks of soil and organic material were removed and the material separated into layers. The 1- to 5-cm-thick litter and partially decomposed organic layers (designated "litter") were separated from the well-decomposed 5- to 10-cm-thick humus layer ("humus"). Soil fauna were sampled at two depths, 0-3 cm and 3-6 cm. Samples were maintained at 4°C until analyses were complete, which was usually the following day.

### Microflora determinations

Ten grams of litter or humus from the treated and control sites were blended in 90 mL sterile distilled $H_2O$ for 3 x 15 s bursts at high speed alternating with 15 s rest periods. Dilutions to $10^{-4}$ were prepared in 9-mL saline blanks and 0.1 mL was planted in duplicate on selective media and incubated at 20°C. Moisture content of samples was determined by drying 1-15 g of sample for 48 h at 85-100°C. The number of organisms was calculated per g dry weight of litter or humus.

Total bacterial counts were determined after 9 days growth on 0.3% TSA agar. Total fungi were determined after 9 days growth on pH 4.5 Czapek-Dox agar. Actinomycetes were determined after

9 days growth on Difco actinomycete agar containing 5 mg/L tetracycline and 50 mg/L cycloheximide. $N_2$ fixers were determined after 14 days growth on mannitol N-free agar. Nitrifying bacteria were determined by the most probable number method using media and incubation conditions as described by Schmidt and Belser (1982). Since this latter method requires a large number of tubes, Nitrobacter activity was monitored in the long-term study and Nitrosomonas in the short-term study.

### Faunal determinations

Two 9-cm-deep soil cores were taken from each of the sampling plots, the cores were divided into three 3-cm layers and stored at 5°C prior to either a wet or dry extraction. Soil animals in the extracts were counted using a dissecting microscope and numbers expressed on a per $m^2$ basis.

Nematodes and enchytraeids were extracted by placing layers from one core on Baerman funnels (Southwood 1978, p. 189) and adding and collecting water every 2 days for 1 week. Samples were preserved in 75% ethanol prior to counting. Soil microarthropods were extracted from layers of the second core individually placed on Lussenhop or Murphy funnels for 6 days (Marshall 1974).

### Statistics

All data were plotted on log paper to effect a logarithmic transformation because the data were not normally distributed, the standard deviations varied directly with the mean and the coefficients of variation were between 0.9 and 1.2. This is a common transformation for population data (Snedecor and Cochran 1967, p. 329). Log transformed data in the short-term experiment on total bacterial populations were subjected to a two-way analysis of variance with repeated measures, with or without pretreatment population levels as a covariate. The SAS implementation of the General Linear Model (SAS Institute 1985) was used for the analysis. The non-parametric, Wilcoxon 2-sample test (Snedecor and Cochran 1967, p. 128) was used for testing for differences between samples for untransformed soil fauna data.

## RESULTS

### Laboratory Study

Irrespective of the soil depth, ROUNDUP at 50 μg a.i./g had no significant effect on carbon dioxide evolution (Fig. 1a-d). ROUNDUP plus urea showed an apparent stimulation of $CO_2$ evolution, which was not significantly different from control. Similarly, there were no significant effects of ROUNDUP, at either depth, on enzymatic hydrolysis of urea (Table 2), disappearance of ammonium with or without urea (Figs. 2a and 2b respectively) or immobilization of fertilizer N (Fig. 2c). Nitrate-N concentrations remained at low levels, and were also not significantly affected by ROUNDUP (Table 3).

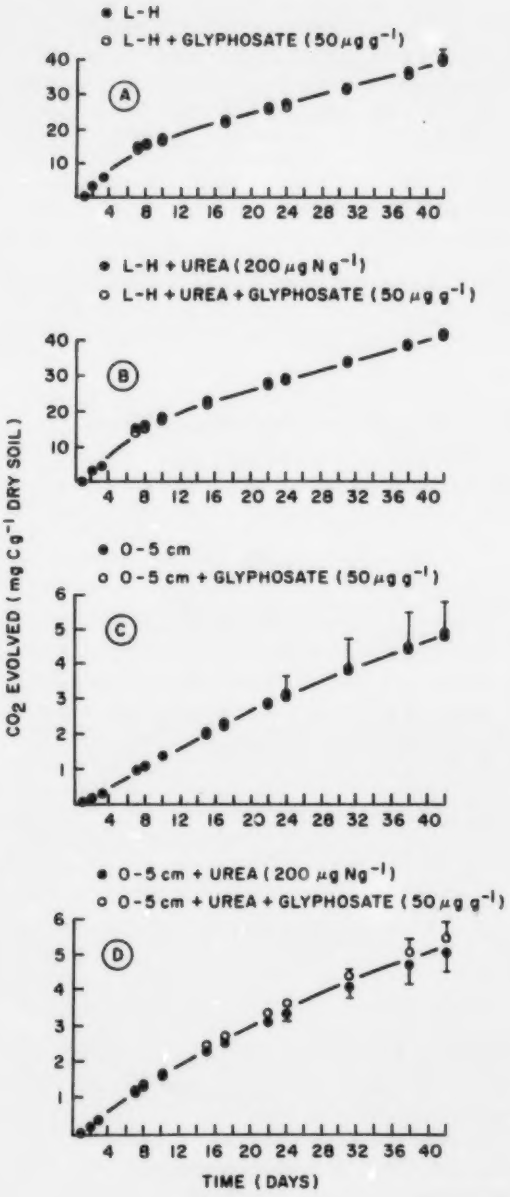


Figure 1. Accumulated $CO_2$ evolution from soil of two depths after different chemical treatments: (a) LH plus ROUNDUP, (b) LH plus urea and ROUNDUP, (c) mineral soil plus ROUNDUP and (d) mineral soil plus urea and ROUNDUP. Vertical bars represent standard deviations.

Table 2. Concentrations of NH$^+$ (mg N/g) 2 days after addition of urea (200 $\mu$g N/g) with and without ROUNDUP (50 $\mu$g a.i./g to LH and 0-5 cm mineral soil from Shawnigan Lake. Values within the LH and 0.5 cm depths were not significantly different at the 0.05 level

| Treatment | LH | Depth<br>0-5 cm |
|---|---|---|
| Urea | 105 | 192 |
| Urea + ROUNDUP | 125 | 188 |

Table 3. Mean nitrate concentrations over time ($\mu$g N/g) for incubation of Shawnigan Lake soil with urea (200 $\mu$g N/g and/or ROUNDUP (50 $\mu$g a.i./g). Abbreviations: LH, organic horizon; 0-5, mineral horizon; U, + urea; G, +ROUNDUP

| Day | 2 | 7 | 14 | 21 | 42 |
|---|---|---|---|---|---|
| Treatment | | | | | |
| LH[a] | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| LHU[b] | 0.10 | 0.10 | 0.10 | 0.10 | 0.11 |
| LHG[c] | 0.10 | 0.10 | 0.13 | 1.03 | 0.10 |
| LHUG | 0.10 | 0.10 | 0.12 | 0.10 | 0.12 |
| 0-5[d] | 0.10 | 0.10 | 0.11 | 1.58 | 0.14 |
| 0-5 U | 0.10 | 0.10 | 0.13 | 0.16 | 0.19 |
| 0-5 G | 0.10 | 0.10 | 0.26 | 1.01 | 0.10 |
| 0-5 UG | 0.10 | 0.10 | 0.13 | 0.31 | 0.13 |

[a] organic horizon
[b] + urea
[c] + ROUNDUP
[d] mineral horizon

### Long-term Field Study

Populations of soil organisms were lower by up to an order of magnitude in the deeper soil depths irrespective of site or treatment. Similar seasonal population fluctuations occurred in lower and upper depths (e.g., total bacteria and nematodes, Fig. 3). For brevity, therefore, only data on populations in the litter layer will be presented.

Total bacterial populations (Fig. 3a) in the litter layer ranged from $10^8$ to $10^9$/g, an order of magnitude higher than in the humus layer. Mean numbers of bacteria in treated plots were lower than in control plots prior to and after spraying. In all plots and sites (Fig. 4a), populations increased over the first 2 months and then stabilized. This increase was most likely due to

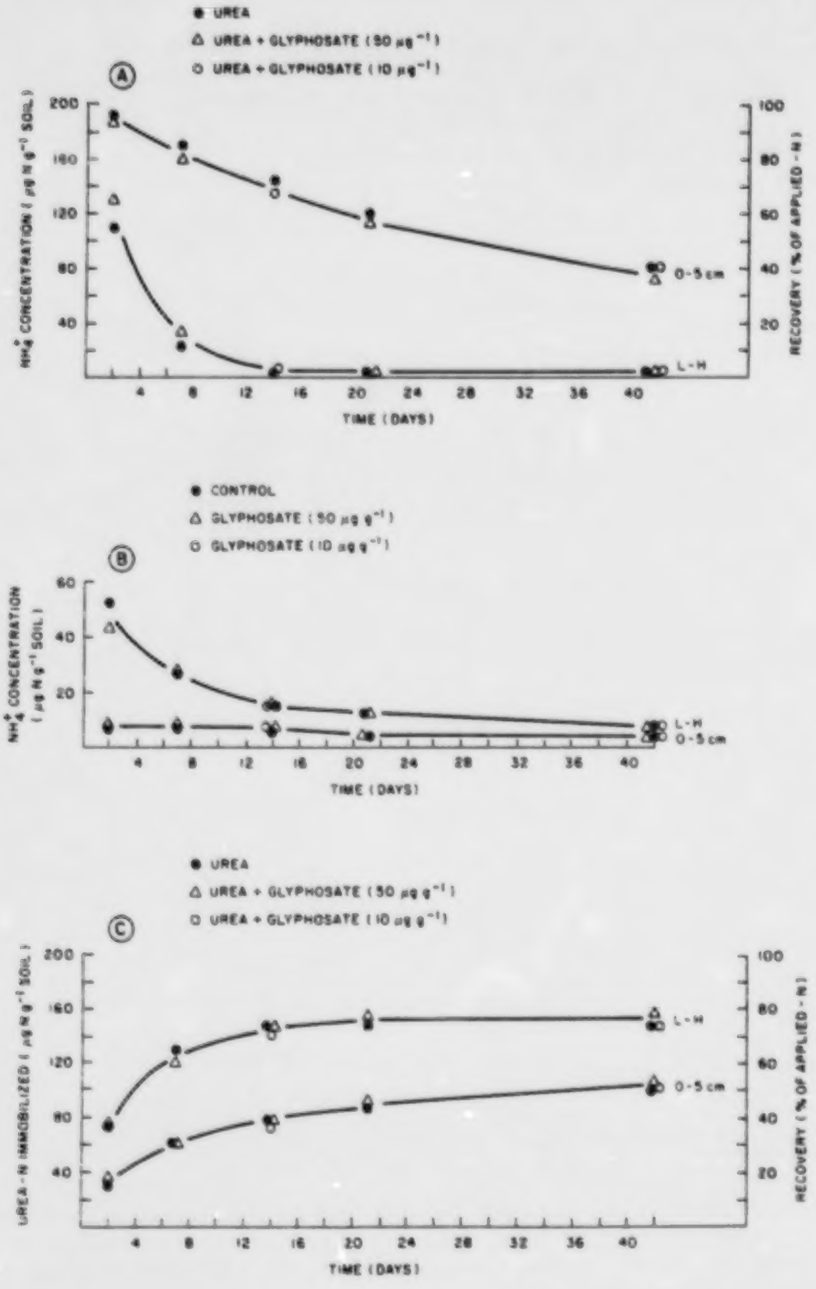


Figure 2. Nitrogen transformations in LH and mineral soils after different chemical treatments. Vertical bars represent standard deviations. (a) Disappearance of ammonium after ROUNDUP plus urea addition. (b) Disappearance of ammonium after ROUNDUP addition. (c) Immobilization of 15N-labelled urea with and without ROUNDUP.

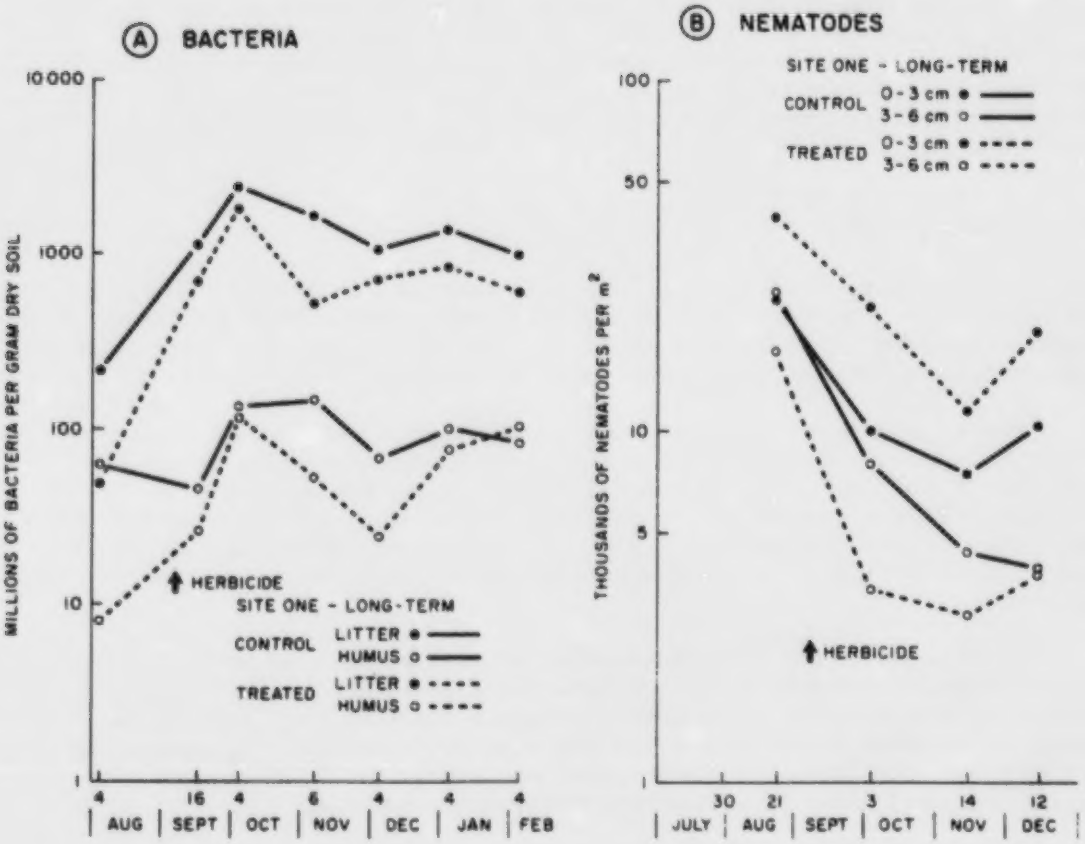


Figure 3. Similarities in the 6-month seasonal population dynamics within litter and humus layers of ROUNDUP treated and untreated plots located in spray block 1 at Carnation Creek: (a) bacteria in litter and humus layers and (b) nematodes at 0-3 cm and 3-6 cm depths. Mean values are plotted on a logarithmic scale.

the onset of fall rains and increasing soil moisture in the litter layer (gravimetric): 40% August 4, 72% August 27, 412% September 16, 270% October 4, and 334% November 6. Numbers of fungal propagules varied by two orders of magnitude between sites and plots prior to spraying and showed considerable seasonal fluctuation (Fig. 4b). No effects of ROUNDUP were observed in spray block 1, while populations in spray block 2 declined for 2 months after spraying before recovering to control levels. Actinomycetes showed a general decline over the season with considerable seasonal and site to site variation (Fig. 4c). Dinitrogen fixer populations (Fig. 4d) showed similar patterns of seasonal fluctuation in both sites and treatments. Reduced numbers occurred at one sampling 3 months after treatment followed by a recovery to control values. Populations of nitrifying bacteria were very low (0-15/10 g), approaching the resolution of the technique, and so no treatment effects were observed. There was a tendency for the nitrifier populations to be twice as high in the wetter humus layers than in the litter layers.

For the soil fauna, populations of soil nematodes (Fig. 3b) declined over the season irrespective of depth, treatment or site (Fig. 5a). Collembolan seasonal population dynamics (Fig. 5b) differed between sites but were similar between treatments considering the initial pretreatment population size. Oribatid and non-oribatid mite populations (Figs. 5c and 5d, respectively) generally increased from August to October though the increase was delayed by 1 month in the site 1 treated plot.

**Short-term Field Study**

Only microflora populations in spray block 1 were examined in the short-term study. As in the long-term study, populations of bacteria, fungi and $N_2$ -fixers were consistently lower at the deeper soil depth (Fig. 6). All microflora populations in both treatments and depths showed an unexplained temporary reduction 3 days after the start of the experiment.

Within a depth, treated and untreated bacterial populations had similar seasonal dynamics (Figure 6a). A complete statistical analysis on total bacterial populations showed no significant main effect of ROUNDUP when pretreatment population levels were used as a covariate (no covariate: F= 7.07, p=0.029 vs. covariate: F=5.36, p=0.054). Seasonal population dynamics data were fit by a sixth-order polynomial (covariate: F=7.39, p=0.030). The main effect of depth was highly significant (F=53.44, p= 0.0002). No significant depth by treatment or depth by time interactions occurred.

Fungal populations (Fig. 6b) fluctuated considerably in all treatments and depths. Populations in treated plots were temporarily reduced below control levels 10-25 days after spraying in the litter but not in the humus. Within a depth, actinomycete (Fig. 6c) and $N_2$ - fixer (Fig. 6d) populations had similar seasonal dynamics with large decreases in all treatments and depths during the first 3 days. Litter populations initially declined more in treated than in untreated plots but recovered after 25 days. Humus populations were unaffected by ROUNDUP.

## DISCUSSION

**Laboratory Study**

The results of the laboratory study of nitrogen transformations and respiration were consistent with previous studies, in that the effects of glyphosate (or ROUNDUP) on soil micro-

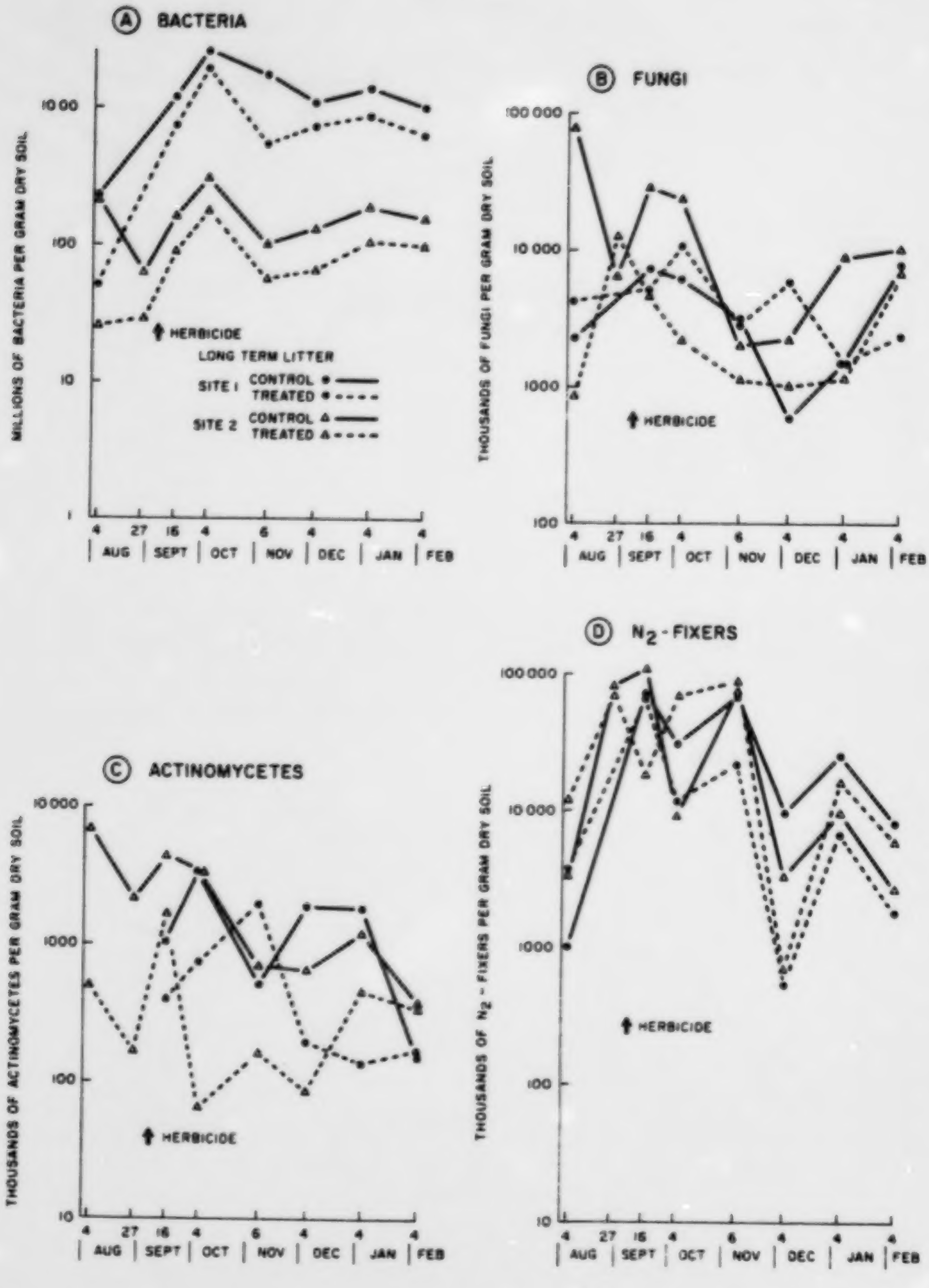


Figure 4. Differences and similarities in site-specific 6-month seasonal population dynamics of (a) bacteria, (b) fungi, (c) actinomycetes and (d) dinitrogen fixers in litter layers of ROUNDUP-treated and untreated plots located in spray blocks 1 and 2 at Carnation Creek. Mean values are plotted on a logarithmic scale.

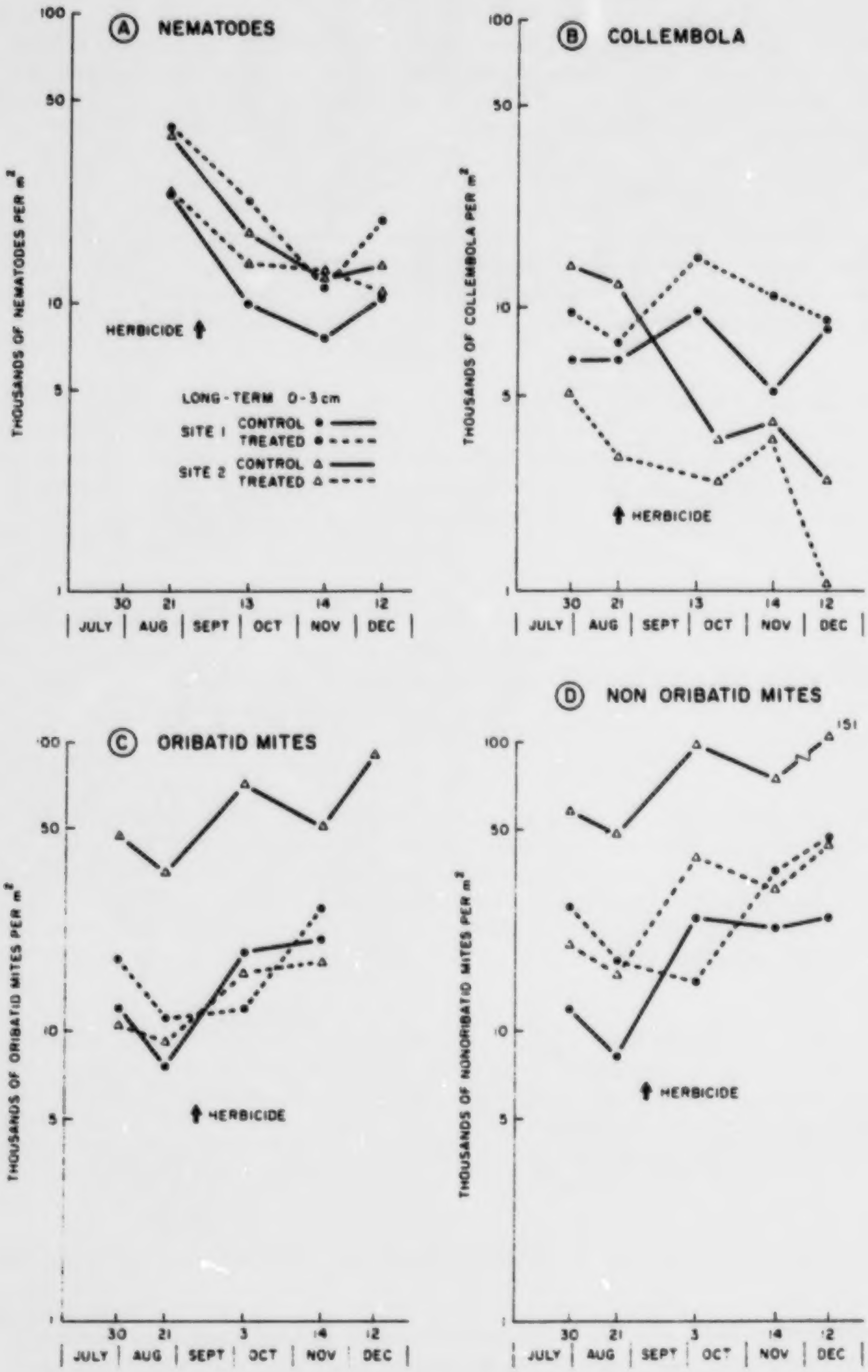


Figure 5. Differences and similarities in site-specific 6-month seasonal population dynamics of (a) nematodes, (b) collembola, (c) oribatid mites and (d) non-oribatid mites in the upper 3 cm of ROUNDUP-treated and untreated plots located in spray blocks 1 and 2 at Carnation Creek. Mean values are plotted on a logarithmic scale.

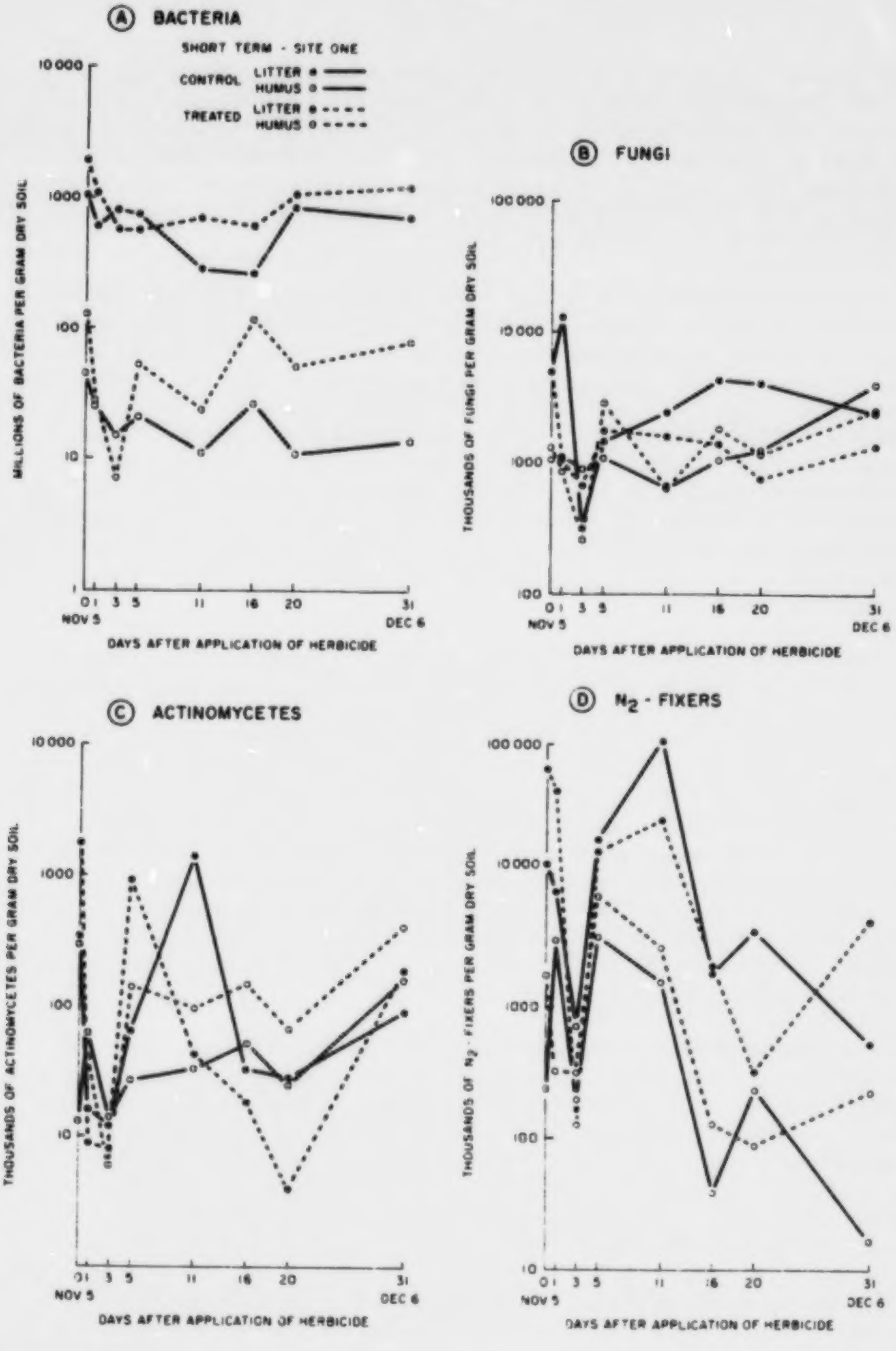


Figure 6. Short-term changes in the populations of: (a) bacteria, (b) fungi, (c) actinomycetes and (d) dinitrogen fixer populations in litter and humus layers of ROUNDUP-treated and untreated plots located adjacent to spray block 1 at Carnation Creek. Mean values are plotted on a logarithmic scale.

flora have generally been found to be small, inconsistent, short-term, or below significance levels. That is because glyphosate is usually quickly inactivated in soil through a combination of binding to soil components (Sprankle et al. 1975a), and degradation. The latter occurs largely through microbial rather than chemical mechanisms (probably by co-metabolism), and its rate can vary a great deal depending on the strength of binding to the soil and the level of soil microbial activity (Müller et al. 1981; Nomura and Hilton 1977; Rueppel et al. 1977; Sprankle et al. 1975b; Tortensson 1985; Tortensson and Aamisepp 1977).

Several mechanisms appear to function in the binding of glyphosate to soil. Through its phosphonic acid moiety, glyphosate binds weakly to unoccupied phosphate binding sites of clay or soil organic matter, and can be displaced by phosphate (Hance 1976). The binding is also affected by the cations present, so that glyphosate is bound more strongly by clays and organic matter saturated with $Al_{3}^{+}$ and $Fe_{3}^{+}$, than with $Na^{+}$, $K^{+}$ or $Ca_{2}^{+}$ (Glass 1987; Hensley et al. 1978; Sprankle et al. 1975b). Sprankle et al. (1975b) suggested that glyphosate forms complexes of phosphonic acid-metal-soil organic matter, similiar to the complexes formed by fulvic acid and orthophosphate with aluminum or ferric chloride (Lévesque and Schnitzer 1967). Thus, inactivation of glyphosate may be expected with suitable combinations of clay or organic matter, available phosphate binding sites, and the presence of iron and aluminum, the latter being enhanced at low pH. The converse is that conditions which lead to strong binding in the soil also tend to slow down microbial degradation.

Several studies have been carried out on the effects of glyphosate or ROUNDUP on soil microbial activity, but there are significant problems in carrying out these studies, and relating the results to field conditions. The effects may be smaller than the natural variations found in the field (Wingfield et al. 1977). There are also many possible indicators that might be used to assess the response of microbial populations to herbicide (Grossbard and Davies 1976). One measure commonly used is respiration (as measured either by oxygen uptake or carbon dioxide evolution), but it is only one indicator of overall microbial activity, and may not be sufficient (Nannipieri et al. 1978). Measurement of gross $O_2$ consumption or $CO_2$ evolution will not reveal whether compensatory population shifts have occurred, as was found, for example, by Mekwatanakarn and Sivasithamparam (1987) in a study of several herbicides including glyphosate. A full protocol to examine effects of pesticide on microbial activity, such as that developed at Jealott's Hill Research Station includes several tests of C and N turnover, as well as direct measurements of microbial biomass and activity (Johnen and Drew 1977).

Once a limited set of tests have been selected, the handling of the soil sample is a critical aspect. Most results (including those in the present laboratory study) are derived from laboratory incubations of soil that has been fully or partially air-dried, and at least coarsely sieved to remove fauna and plant material, followed by thorough mixing of the pesticide into the soil at recommended and excessive levels. These conditions are generally chosen to give reproducible results, and also to maximize the effects on the microflora. It has been shown, however, that the effects of dalapon (2,2-dichloropropionic acid) on soil microflora were less in undisturbed soil cores sprayed with dalapon, than in air-dried samples in which the dalapon had been thoroughly mixed (Wingfield et al. 1977). Similarly, the effects of excessive levels of dalapon on nitrogen transformations were markedly influenced by temperature and moisture (Marsh and Greaves 1979). While there is continuing controversy over the treatment and handling of soil samples in chemical and microbiological studies, it is usually preferable to minimize disturbance due to air-drying, sieving or grinding. It is also usually desirable that samples be used in a field-moist state, or stored at 4°C until use, subjected to a minimum of sieving and grinding, and allowed to equilibrate for 7-10 days at the temperature and moisture chosen for the study before addition of study materials. There are also arguments for the use of intact soil cores; these will inevitably give wider variation in the results, but will mimic field conditions more closely. These limitations should be kept in mind in the following discussion.

Marsh et al. (1977) examined the effect of 100 μg a.i./g glyphosate on respiration and nitrogen transformation in two soils. The effects on respiration -- both stimulation and inhibition -- were small, and disappeared by 18 weeks. Nitrogen mineralization, which was studied for 10 weeks, was stimulated by glyphosate in both soils. It could not be determined whether this increase was due to increased activity of the nitrifying organisms, or to release of nitrogen from the breakdown of the herbicide.

Marsh (1985) also investigated the possible effects of herbicide-fertilizer interactions on nitrogen and phosphorus transformations in the soil. At 20 μg a.i./g glyphosate, he found no effects in the absence of fertilizer. With fertilizer, there was a small initial stimulation of mineralization (total ammonium plus nitrate). Glyphosate also had a short-term effect on available P, by largely preventing the initial reduction in available P that occurred after fertilizer application. This may have been due to glyphosate occupying phosphate binding sites in the soil. The soil was chosen for its possible sensitivity to herbicide, as it had a high sand content, and a low pH (4.9 in water), which might be further lowered by the addition of fertilizer.

Müller et al. (1981) examined the decomposition of glyphosate, and its influence on nitrogen-cycling in two Finnish agricultural soils prior to establishment of tree plantations. In a long-term field experiment (up to 249 days), degradation was slow, especially in the mineral soil. No significant effects of glyphosate were found on the soil potential for acetylene reduction (nitrogen fixation), nitrification and denitrification, as determined in laboratory incubations of soil samples. Some small effects observed may have been due more to changes in plant cover than to direct effects of glyphosate. Unfortunately, this study did not include control sites, and measurements of soil available N at each sampling.

One cause for concern is the possible effect of residual glyphosate on nitrogen-fixing organisms. Eberbach and Douglas (1983) found deleterious effects on nitrogen fixation (decreases in nodule numbers, acetylene reduction and root weights) in clover planted 120 days after addition of glyphosate to a sandy loam. The soil contained 82% sand, 5% silt, 13% clay, and only 0.35% organic C. The combination of high sand, low clay, very low organic matter, and high pH (7.3 in water) would be unfavourable for binding and inactivation of glyphosate in this soil.

The extracellular enzymes of soil are a possible locus of pesticide action. These enzymes are secreted by microorganisms, and remain in the soil. They are important in breaking down large molecules and polymers into small units that can pass through the cell walls. A study of the effect of glyphosate and three other herbicides on dehydrogenase, phosphatase and urease also found no significant effects on enzymatic activity (Davies and Greaves 1981). These authors concluded that enzyme assays are unsuitable for assessing the effects of pesticides on the soil ecosystem, especially for registration purposes. This is because of the large natural variation in enzyme activities and their extreme sensitivity to environmental conditions. Further, phosphatase and dehydrogenase are actually two groupings of a wide range of soil enzymes with similiar properties and functions.

Generally, herbicides have not been found to have long-term harmful effects on measured parameters of microbial activity, especially at recommended rates of application (Goring and Laskowski 1982; Greaves et al. 1976; Kimmins 1975; Wainwright 1978), and when studied in direct comparison with other herbicides, the effects of glyphosate seem especially innocuous. Most studies were carried out in the laboratory, in soil often subjected to disturbances, or on pure cultures of microorganisms. They also usually examined the effects of a single dose of a single herbicide -- conditions which are at least more realistic for forestry than for agriculture. Furthermore, even the "long-term" studies were usually single-dose and extended, at most, to 30-40 weeks, while very few field studies have been carried out.

### Field Studies

The results of the field studies, also consistent with previous studies, indicated no significant long-term effects of glyphosate application. Results from the 6-month experiment suggest that no profound long-term changes in soil microflora or fauna populations could be attributed to the glyphosate application. There were indications that short-term reductions occurred, but these were site-dependent. For example, fungi in site 2, $N_2$ -fixers in spray blocks 1 and 2, and mites in spray block 1 temporarily declined in glyphosate-treated plots.

Short-term study results revealed that in the early period after glyphosate application (up to 20 days) large reductions occurred in some microorganism populations, especially the fungi, actinomycete and $N_2$-fixer populations. These results were most evident in the litter samples as would be expected since glyphosate was applied directly on the surface. Recovery of populations within 30 days revealed the importance of intensive sampling when monitoring the immediate impact of herbicide on soil populations.

Glyphosate, at concentrations similiar to those used in field applications, has generally been reported to have nil or transitory effects on populations of soil microflora (Grossbard 1985) and fauna (Eijsackers 1985). Grossbard (1985) reviewed studies of effects of glyphosate on the microflora and concluded that its effects in plate or solution culture were more intense than in the soil. The few field studies described were concerned with the effects of glyphosate on plant residue decomposition. Neither straw nor leaf litter decomposition were inhibited at applications of 42 kg a.i./ha or 25 $\mu$ a.i./g, respectively.

Applications of 1-50 $\mu$g a.i./g had no effects on fungi, actinomycete or bacteria populations in 214-day laboratory soil incubations (Roslycky 1982; concentrations reported as "$\mu$g of the glyphosate salt per gram of wet soil"). At higher concentrations, 100-1000 $\mu$g a.i./g, populations of fungi, bacteria and actinomycetes, relative to the control, rapidly increased then declined during the first 30 days. For the remainder of the experiment, bacteria and actinomycetes remained at elevated levels while fungi fluctuated at or slightly above control levels. In soil suspensions, respiration by bacteria and actinomycetes was inhibited at high glyphosate concentrations while fungi were unaffected. Replica plating onto agar containing increasing glyphosate concentrations (10-1000 $\mu$g a.i./mL) demonstrated selective growth inhibition of bacterial and actinomycete isolates. For example, at 50 $\mu$g a.i./mL, only 52% of the bacteria iosolates grew while all actinomycete isolates grew.

A review of glyphosate effects on soil fauna (Eijsackers 1985) concluded that the field studies reported to date indicate effects are small and transitory or entirely absent. Longevity of collemboles (*Onychiurus quadriocellatus* and *Tomocerus flavescens*) and isopods (*Philoscia muscorum* and *Oniscus asellus*) was reduced 15 and 30% respectively in laboratory cultures sprayed with glyphosate at 0.22 g a.i./m. Longevity of the mite, Pergalumna sp. (Hoy et al. 1982) and the earthworm, *Allolobophora caliginosa*, (Martin 1982) were unaffected at glyphosate applications of 0.22 g a.i./m and 1000 $\mu$g a.i./g respectively.

# CONCLUSIONS

The results of these laboratory and field studies of soil fauna and microflora did not contradict previous work. The effects of ROUNDUP were found to be small, transient, and less than variations caused by environmental factors such as moisture. Several suggestions can be made for further research. Few field studies have been carried out on the effects of glyphosate (ROUNDUP) on soil fauna and microflora. There also has been little work on forest soils or the environmental conditions particular to British Columbia. Further work is required on the effects of glyphosate on microbial and faunal activity, and on glyphosate degradation (which is regulated by microbial activity) under conditions of varying temperature, moisture (including periods of saturation), with different soil types, as well as in the field. Most studies of the binding and degradation of glyphosate have been carried out on agricultural soils; little is known of its fate in the various horizons found in the forests of British Columbia. These include litter, poorly developed gravelly soils, and the combinations of silt and gravel beds found in floodplains.

Since the effects of glyphosate on biological activity of soils are usually small and transient, studies should have very sound statistical design, and include both intensive short-term and less frequent long-term sampling. The large site to site and seasonal variations require that future studies include appropriate statistical treatment of the data to remove pretreatment and seasonal affects from those due to the treatment. For field studies, the use of composite samples may be a useful alternative to analysing huge numbers of samples (Carter and Lowe 1986). Also, since the effects of glyphosate are usually difficult to separate from those due to vegetation kill, field studies should now begin to address this question. This would require plots with vegetation killed manually and left to decompose, with and without glyphosate. Such field studies should be supplemented with laboratory studies on soil samples taken from the same site, and treated appropriately to minimize disturbance. The laboratory studies are essential supplements to the field ones, to provide more precise data on trends observed in the field, and to inquire more closely into the mechanisms involved.

Glyphosate contains nitrogen, and stimulation of mineralization or nitrification has sometimes been observed after glyphosate application (Marsh 1985; Marsh et al. 1977). It is not known whether the increase in mineral N is due to stimulation of soil processes, or includes a contribution from the glyphosate N. No studies of the fate of the N in glyphosate have been carried out, and this could be done using 15N-labelled glyphosate. The amounts of labelled N would be too small for analysis by mass spectrometry (0.5-1.0 mg total N required), but could be carried out easily using optical emission analysis of 15N enrichment, for samples down to 5 $\mu$g total N (Preston et al. 1981). While this effect may be small, quantification of nitrate release after glyphosate treatment is essential for modelling the biogeochemical effects, and assessing the relative impacts of different methods of site preparation and vegetation control. Similarly, while laboratory studies indicate that glyphosate binds less strongly than phosphate to soil, laboratory studies (Marsh et al. 1977) have detected increases in available phosphate after glyphosate treatment. Quantification of these processes, and clarification of the mechanisms would aid in assessing biogeochemical effects of glyphosate treatment.

Current methods of analysis for glyphosate or its metabolites are tedious and time-consuming, and this has hindered more widespread analysis of glyphosate residues. Reuppel et al . (1977) demonstrated the feasability of using 13C, 31P and 1H NMR analysis, at least for laboratory studies. Since 1977, there have been enormous improvements in NMR analytical capability. Thus, it would now be worthwhile to develop NMR techniques, especially for laboratory studies, for studies with labelled glyphosate, and for investigations of the mechanism of binding of glyphosate to soil and litter, and its exchange with phosphate.

## ACKNOWLEDGEMENTS

The study of respiration and nitrogen transformations in the Shawnigan Lake soil was carried out by Liesbet Croockewit at the University of British Columbia, under the supervision of Dr. P. C. K. Pang, Pacific Forestry Centre. Microbial populations at Carnation Creek were analysed by Dr. W. W. Kay, through a contract with Microtek Research and Development Limited, Victoria. The faunal study was undertaken under contract by Dr. A. Carter at the University of British Columbia. We thank them for their contributions, and we also thank Kevin McCullough and Ann Van Niekerk of the Pacific Forestry Centre for technical assistance. The two contracts were let under the Intensive Forestry Management Subsidiary Agreement of the Canada/British Columbia Forest Resource Development Agreement.

## REFERENCES

Carter, R.E. and L.E. Lowe. 1986. Lateral variability of forest floor properties under second-growth Douglas-fir stands and the usefulness of composite sampling techniques. Can. J. For. Res. 16:1128-1132.

Crown, M. and C.P. Brett. (eds.). 1975. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: an establishment report. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C., Inf. Rep. BC-X-110, 45 p.

Davies, H.A. and M.P. Greaves. 1981. Effects of some herbicides on soil enzyme activities. Weed Res. 21:205-209.

Eberbach, P.L. and L.A. Douglas. 1983. Persistence of glyphosate in a sandy loam. Soil Biol. Biochem. 15:485-487.

Eijsackers, H. 1985. Effects of glyphosate on the soil fauna. Pages 151-158 in E. Grossbard and D. Atkinson, (eds.). The Herbicide Glyphosate. Butterworths.

Glass, R.L. 1987. Adsorption of glyphosate by soils and clay minerals. J. Agric. Food Chem. 35: 497-500.

Goring, C.A.I. and D.A. Laskowski. 1982. The effects of pesticides on nitrogen transformations in soils. Pages 689-720 in Nitrogen in Agricultural Soils - Agronomy Monograph no. 22, American Society of Agronomy, Inc. and Soil Science Society of America, Inc., Madison, Wisconsin.

Greaves, M.P., H.A. Davies, J.A.P. Marsh and G.I. Wingfield. 1976. Herbicides and soil microorganisms. C.R.C. Crit. Rev. Microbiol. 5:1-38.

Grossbard, E. 1985. Effects of glyphosate on the microflora: with reference to the decomposition of treated vegetation and interaction with some plant pathogens. Pages 159-185 in E. Grossbard and D. Atkinson (eds.). The Herbicide Glyphosate. Butterworths, London.

Grossbard, E. and H.A. Davies. 1976. Specific microbial responses to herbicides. Weed Res. 16: 163-169.

Hance, R.J. 1976. Adsorption of glyphosate by soils. Pestic. Sci. 7: 363-366.

Hensley, D.L., D.S.N. Beuerman and P.L. Carpenter. 1978. The inactivation of glyphosate by various soils and metal salts. Weed Res. 18:287-291.

Hoy J.B., D.L. Dahlsten and P.J. Shea. 1982. The effects of 2,4-D and an alternative material (glyphosate) used for brushfield rehabilitation of soil arthropod community and litter decomposition rate. Final Report USA-UCB, Research Agreement No. PSW-81-0026.

Johnen, B.G. and E.A. Drew. 1977. Ecological effects of pesticides on soil microorganisms. Soil Sci. 123:319-324.

Kimmins, J.P. 1975. Review of the ecological effects of herbicide usage in forestry. Environ. Can., Can. For. Serv. Pac. For. Res. Cent., Victoria, B.C., Inf. Rep. BC-X-139, 44 p.

Lévesque, M. and M. Schnitzer. 1967. Organo-metallic interactions in soils: 6. Preparation and properties of fulvic acid-metal phosphates. Soil Sci. 103:183-190.

Marsh, J.A.P. 1985. Effects of herbicide-fertilizer interactions on nitrogen and phosphorus transformations and herbicide persistence in soil. Pestic. Sci. 16:93-100.

Marsh, J.A.P., H.A. Davies and E. Grossbard. 1977. The effect of herbicides on respiration and transformation of nitrogen in two soils. I. Metribuzin and glyphosate. Weed Res. 17:77-82.

Marsh, J.A.P. and M.P. Greaves. 1979. The influence of temperature and moisture on the effects of the herbicide dalapon on nitrogen transformations in soil. Soil Biol. Biochem. 11:279-285.

Marshall V.G. 1974. Seasonal and vertical distribution of soil fauna in a thinned and urea-fertilized Douglas-fir forest. Can. J. Soil Sci. 54:491-500.

Martin N.A. 1982. The effects of herbicides used on asparagus on the growth rate of the earthworm *Allolobophora caliginosa*. Pages 328-331 in Proceedings of the 35th New Zealand Weed and Pest Control Conference.

Mekwatanakarn, P. and K. Sivasithamparam. 1987. Effect of certain herbicides on soil microbial populations and their influence on saprophytic growth in soil and pathogenicity of take-all fungus. Biol. Fert. Soils. 5: 175-180.

Müller, M.M., C. Rosenberg, H. Siltanen and Wartiovaara. 1981. Fate of glyphosate and its influence on nitrogen-cycling in two Finnish agricultural soils. Bull. Environm. Contam. Toxicol. 27:724-730.

Nannipieri, P., R.L. Johnson and E.A. Paul. 1978. Criteria for measurement of microbial growth and activity in soil. Soil Biol. Biochem. 10:223-229.

Nomura, N.S. and H.W. Hilton. 1977. The adsorption and degradation of glyphosate in five Hawaiian sugarcane soils. Weed Res. 17:113-121.

Pang, P.C.K. amd K. McCullough. 1985. Preparation of soil and plant materials for N-isotope analysis by mass spectrometer. Can. For. Serv., Internal Report, Pac. For. Res. Cent., Victoria, B.C. 26 p.

Preston, C.M., J.M. Preston and E.G. Callway. 1981. Inexpensive 15N analysis of agricultural samples by optical emission spectroscopy employing a simple one-step Dumas sample preparation procedure. Can. J. Spectrosc. 26:239-244.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. Overview of Carnation Creek herbicide project; historical perspective, experimental protocols and spray operations. This Proceedings.

Roslycky. 1982. Glyphosate and the response of the soil microbiota. Soil Biol. Biochem. 14:87-92.

Rueppel, M.L., B.B. Brightwell, J. Schaefer and J.T. Marvel. 1977. Metabolism and degradation of glyphosate in soil and water. J. Agric. Food Chem. 25:517-528.

SAS Institute Inc. 1985. SAS User's Guide: Statistics, Version 5 Edition. SAS Institute Inc. Cary, NC. 956 pp.

Schmidt, E.L. and L.W. Belser. 1982. Nitrifying bacteria. Pages 1027-1042 in A.L. Page (ed.). Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, Agronomy Monograph no. 9. Soil Science Society of America, Inc. Madison, Wisconsin.

Snedecor, G.W. and W.G. Cochran. 1967. Statistical Methods. Iowa University Press. Ames, Iowa.

Southwood, T.R.E. 1978. Ecological Methods. Chapman and Hall. London.

Sprankle, P., W.F. Meggitt and D. Penner. 1975a. Rapid inactivation of glyphosate in the soil. Weed Sci. 23:224-228.

Sprankle, P., W.F. Meggitt, and D. Penner. 1975b. Adsorption, mobility and microbial degradation of glyphosate in the soil. Weed Sci. 23:229-234.

Tortensson, L. 1985. Behaviour of glyphosate in soils and its degradation. Pages 137-150 in E. Grossbard and D. Atkinson, eds. The Herbicide Glyphosate. Butterworths, London.

Tortensson, N.T.L. and A. Aamisepp. 1977. Detoxification of glyphosate in soil. Weed Res. 17:209-212.

Wainwright, M. 1978. A review of the effects of pesticides on microbial activity in soils. J. Soil Sci. 29: 287-298.

White, C.S. and J.R. Gosz. 1981. Organic nitrogen interference with automatic ammonium analyses. Can. J. For. Res. 11:739-741.

Wingfield, G.I., H.A. Davies and M.P. Greaves. 1977. The effect of soil treatment on the response of the soil microflora to the herbicide dalapon. J. Appl. Bact. 43:39-46.

# THREE-YEAR HERBICIDE EFFICACY, CROP TOLERANCE AND CROP GROWTH RESPONSE RESULTS FOR A 1984 GLYPHOSATE CONIFER RELEASE TRIAL AT CARNATION CREEK, BRITISH COLUMBIA

P.E. Reynolds[1], D.G. Pitt[1], R. Whitehead[2] and K. King[2]

[1]Forest Pest Management Institute
1219 Queen Street East
Sault Ste. Marie, Ontario
P6A 5M7

[2] Pacific Forestry Centre
506 West Burnside Road
Victoria, B.C.
V8Z 1M5

## ABSTRACT

In early September 1984, portions of the Carnation Creek Watershed, located on the west coast of Vancouver Island (48°54'N, 125°01'W), were aerially treated with 2 kg ai/ha of glyphosate [N-(phosphonomethyl) glycine] using a Bell-47 helicopter equipped with a MICROFOIL BOOM to minimize herbicide drift into an adjoining salmon-bearing stream. Since 1970, the watershed has been a focal point for interagency cooperative research designed to assess the effects of forest practices (i.e., harvesting, prescribed burning, herbicide use) on resident salmonid fish populations. The present herbicide study was undertaken in support of this overall objective.

Prior to glyphosate treatment, major weed competition consisted of red alder (*Alnus rubra* Bong.) and salmonberry (*Rubus spectabilis* Pursh.). Herbicide efficacy following glyphosate treatment was species dependent, being generally high, one year after treatment, for most species present. Although salmonberry control was quite satisfactory after one post-spray growing season, control of red alder was quite variable, ranging from no control (i.e., completely healthy) to total control (i.e., totally dead). Salal (*Gaultheria shallow* Pursh.) was not controlled by the herbicide treatment. Control of all weed species declined two and three years after treatment.

Some minor crop tree injury resulted following glyphosate treatment for western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] and to a lesser extent for western redcedar (*Thuja plicata* Donn). Initial injury consisted of death or dieback of the primary leader but was not observed for other crop trees [i.e., sitka spruce, *Picea sitchensis* (Bong.) Carr., amabilis fir, *Abies amabilis* (Dougl.) Forbes, and Douglas fir, *Pseudotsuga menziesii* (Mirb.) Franco] present. After one year, trees exhibiting initial injury showed full recovery.

Following glyphosate treatment, sitka spruce and hemlock root-collar diameter and diameter increment increased significantly for trees treated with glyphosate. Had optimal weed control been achieved, even greater growth increases would likely have resulted from the herbicide treatment. In the context of the present environmental impact study, glyphosate is seen to have performed the job it was intended to do and to have provided better than expected silvicultural performance.

## INTRODUCTION

Successful attempts to renew Canada's forests are plagued by a lack of registered forestry herbicides. This lack of registered herbicides is due in large measure to environmental concerns, and the problem is especially acute in British Columbia where notable fisheries resources (i.e., pacific salmon) are located within coastal forest sites that would benefit most from herbicide use. At present only two herbicides, including glyphosate, are fully registered (i.e., inclusive of aerial applications) for forestry use in Canada. One herbicide, hexazinone [3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4 (1H, 3H)-dione], has a temporary registration for ground applications only.

A role of the Canadian Forestry Service is to assist in the collection of environmental impact data, specific to Canadian environmental conditions, needed to fully register additional herbicides or to expedite the use of federally registered herbicides by answering regional environmental concerns, which extend beyond federal registration data requirements. The present herbicide study was undertaken to assess environmental impacts on resident salmonids, and was not initiated to silviculturally evaluate the performance of glyphosate in controlling unwanted coastal weeds or in enhancing crop growth. A sound silvicultural study would have been characterized by a substantially different experimental design, and not constrained by the unique operational and/or environmental parameters of the present experiment.

### Study Area

The Carnation Creek Watershed is located on the west coast of Vancouver Island. The watershed is located near the town of Bamfield on the south side of Barkley Sound (48°54'N, 125°01'W) and is approximately 10 $km^2$ in area. From 1975 to 1981, portions of the watershed were logged (approximately 404 ha), and various post-harvesting silvicultural treatments, inclusive of scarification, prescribed burning and planting, were carried out commencing in the fall of 1976 and continuing through the spring of 1983 (Dryburgh 1982). Crop species planted consisted of sitka spruce [*Picea sitchensis* (Bong.) Carr.], western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], western red cedar (*Thuja plicata* Donn), Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco.], amabilis fir [*Abies amabilis* (Dougl.) Forbes.] and some grand fir [*Abies grandis* (Dougl.) Lindl.]. Notable hemlock, cedar and amabilis fir natural regeneration occurred following harvesting. Post-harvest revegetation of the watershed has been described in detail elsewhere (King and Oswald 1982). Prior to herbicide treatment, major weed competition consisted of red alder and salmonberry.

## MATERIALS AND METHODS

Glyphosate (2 kg ai/ha) was aerially applied to a 45-ha portion of the watershed as described in an accompanying paper (Reynolds et al. 1989). Treatment was performed in September 1984 using a Bell-47 helicopter equipped with a MICROFOIL BOOM[1] to minimize herbicide drift into an adjoining salmon-bearing stream. The watershed was operationally sprayed by dividing the spray area into ten spray blocks easily delineated by natural topographic features. Untreated control areas were located throughout the sprayed watershed, and their locations and boundaries were delineated by orange garbage bags tied to wooden markers or tree tops.

[1] Registered trademark of Union Carbide Inc., Ambler, Pennsylvania.

Efficacy against weeds and crop tolerance were assessed in 1985, 1986 and 1987 by establishing circular vegetation sample quadrats (1.8-m radius for herbaceous plants and 25 m for brush) at 50 - 75 m intervals along transects running throughout the watershed. Sample quadrats were permanently established (36 treated and 5 untreated) in September 1985. Where possible, most transects were located within the watershed valley bottom, since most of the herbicide treatment occurred within the floodplain of Carnation Creek. Changes in transect compass bearing or sampling interval were minimized, and were necessitated by changing terrain features mediated by the natural course of Carnation Creek itself (i.e., the watershed is essentially a ravine, with Carnation Creek flowing through the valley bottom). Efficacy against weeds and crop injury were rated on a scale of 0 to 10; 0 being no control or injury and 10 being total weed kill or maximum crop injury.

If present, one crop tree (sitka spruce, western hemlock and western redcedar) was tagged within a 2-m radius of each permanent transect sample location, and growth measurements (i.e., total height, previous yearly heights and current root collar diameter) were recorded for each tagged specimen in September 1985, 1986 and 1987. Additional trees, at other permanent sample locations within the watershed floodplain, were tagged and monitored for growth response prior to (September 1984) or after glyphosate treatment (September 1985, 1986 and 1987). Both crop growth data sets were pooled to produce the growth data presented in this paper. The actual numbers of trees sampled, which were variable, are presented with the data.

All data was collected using a Polycorder 640 data logger system. The data were later downloaded onto a VAX 8530 main-frame computer where SAS (Statistical Analysis Systems) software was used for subsequent data manipulation, statistical analysis and generation of graphics. Graphics presentations are delineated to distinguish between various types of damage or injury (i.e., herbicide, other, insect, browse). SAS computations using raw data were made to determine incremental height growth and root-collar diameter increment growth for 1987 and previous years.

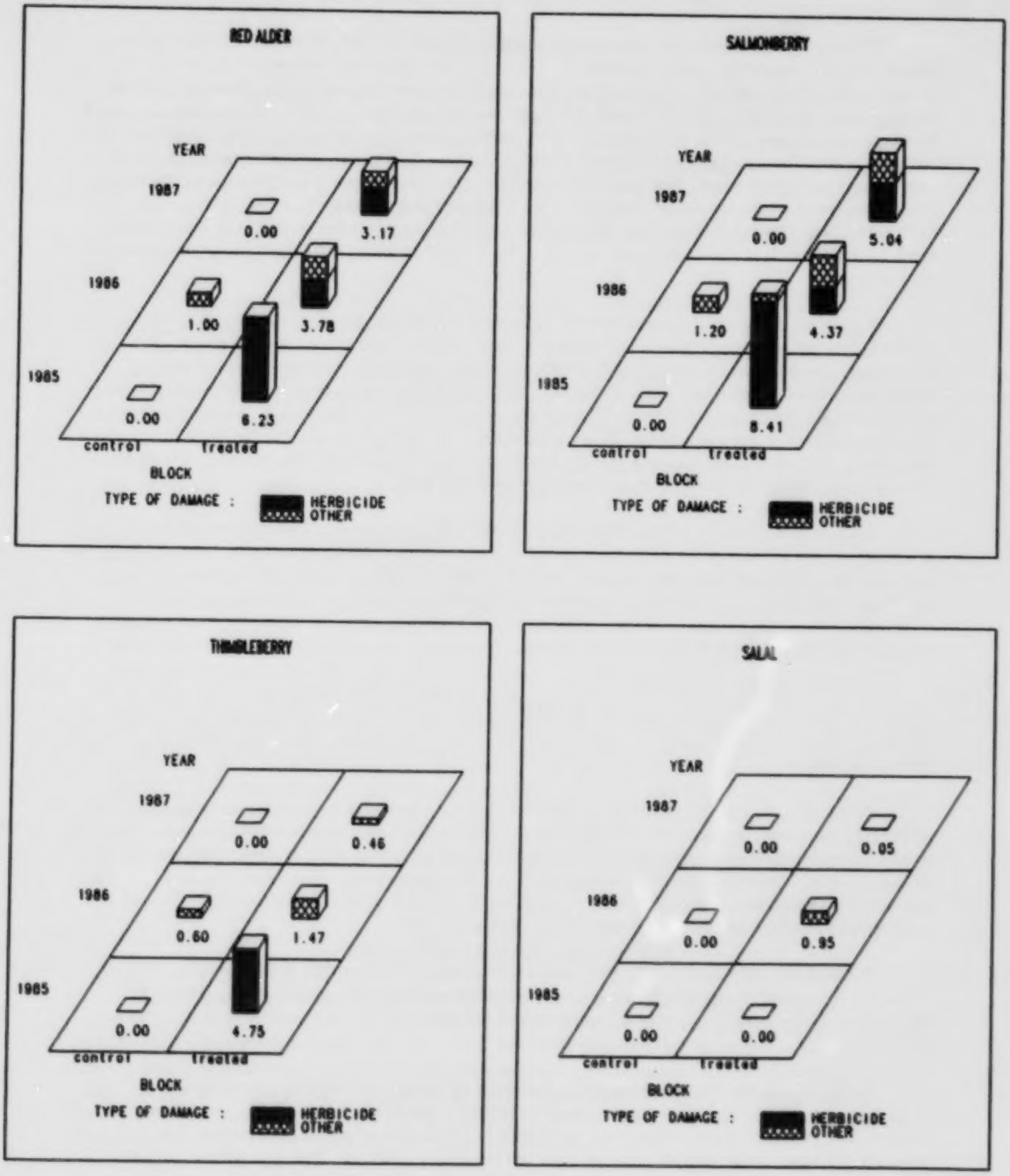
## RESULTS

### Herbicide Efficacy

Herbicide efficacy one year after glyphosate treatment was species dependent, being generally high for most species present (Figures 1-4). Although salmonberry control was quite satisfactory after one post-spray growing season, control of red alder was quite variable, ranging from no control (i.e., completely healthy) to total control (i.e., totally dead). Salal and evergreen huckleberry (*Vaccinium ovatum* Pursh.) were not controlled by the herbicide treatment. Control of most species declined in 1986 and continued to decline in 1987.

A statistical analysis of 1985, 1986 and 1987 herbicide efficacy data is presented in Table 1. A number of statistically significant control values were observed in 1985. However, the number of statistically significant control values declined in 1986 and continued to decline in 1987.

A statistically significant difference in herbicide efficacy for floodplain versus lower slope microsites was observed for three species (Table 2). In 1985, greater alder, swordfern [*Polystichum munitum* (Kaulf) Pres.] and thimbleberry (*Rubus parviflorus* Nutt.) control was observed for lower slope sample quadrats than for floodplain quadrats. For this reason, and also due to a lack of lower slope controls, herbicide efficacy data presented in Table 1 is restricted to floodplain quadrats.



RED ALDER

SALMONBERRY

THIMBLEBERRY

SALAL

Figure 1. Mean health values for major competitors in the floodplain, by species and year of assessment.

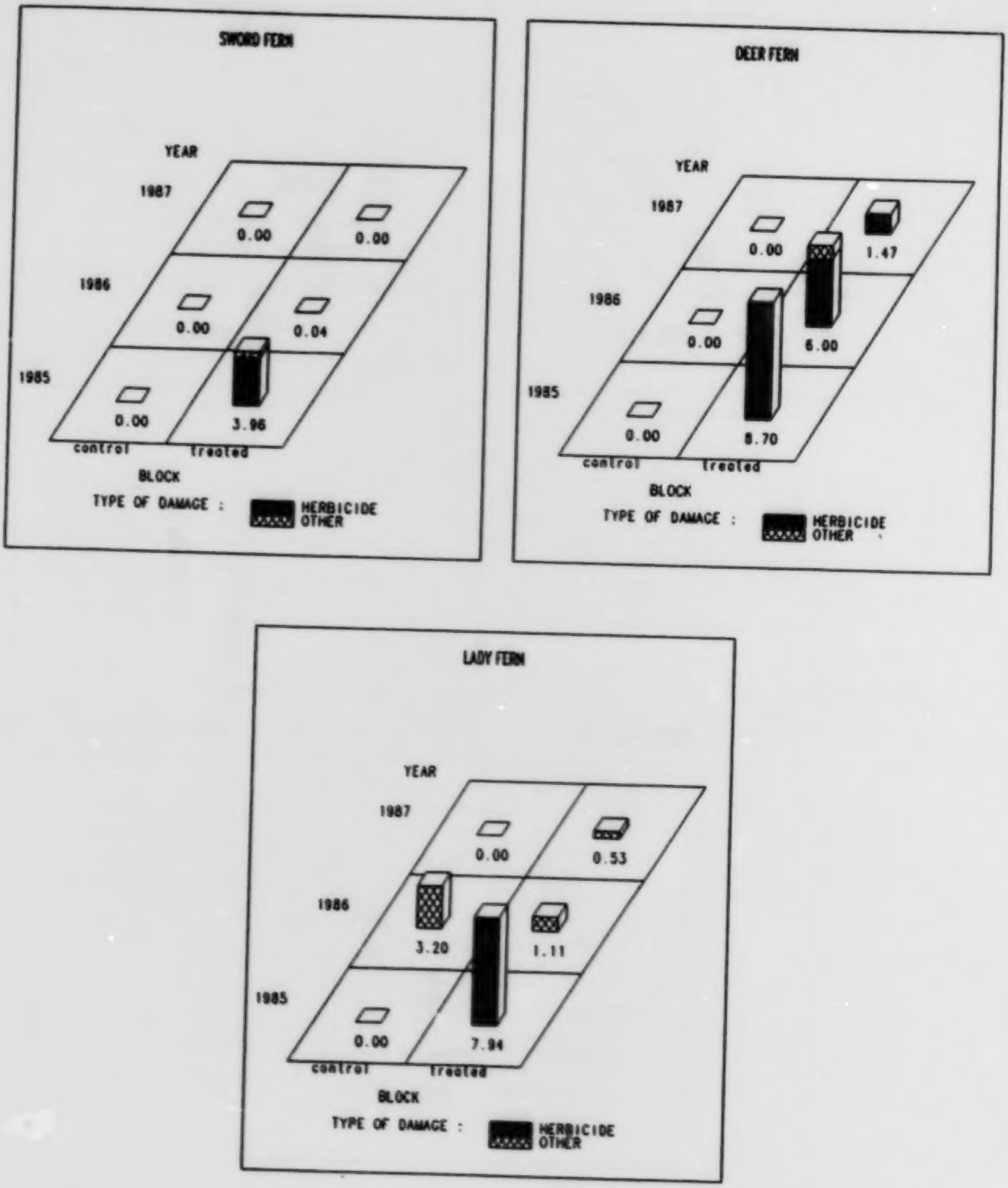


Figure 2. Mean health values for ferns in the floodplain, by species and year of assessment.

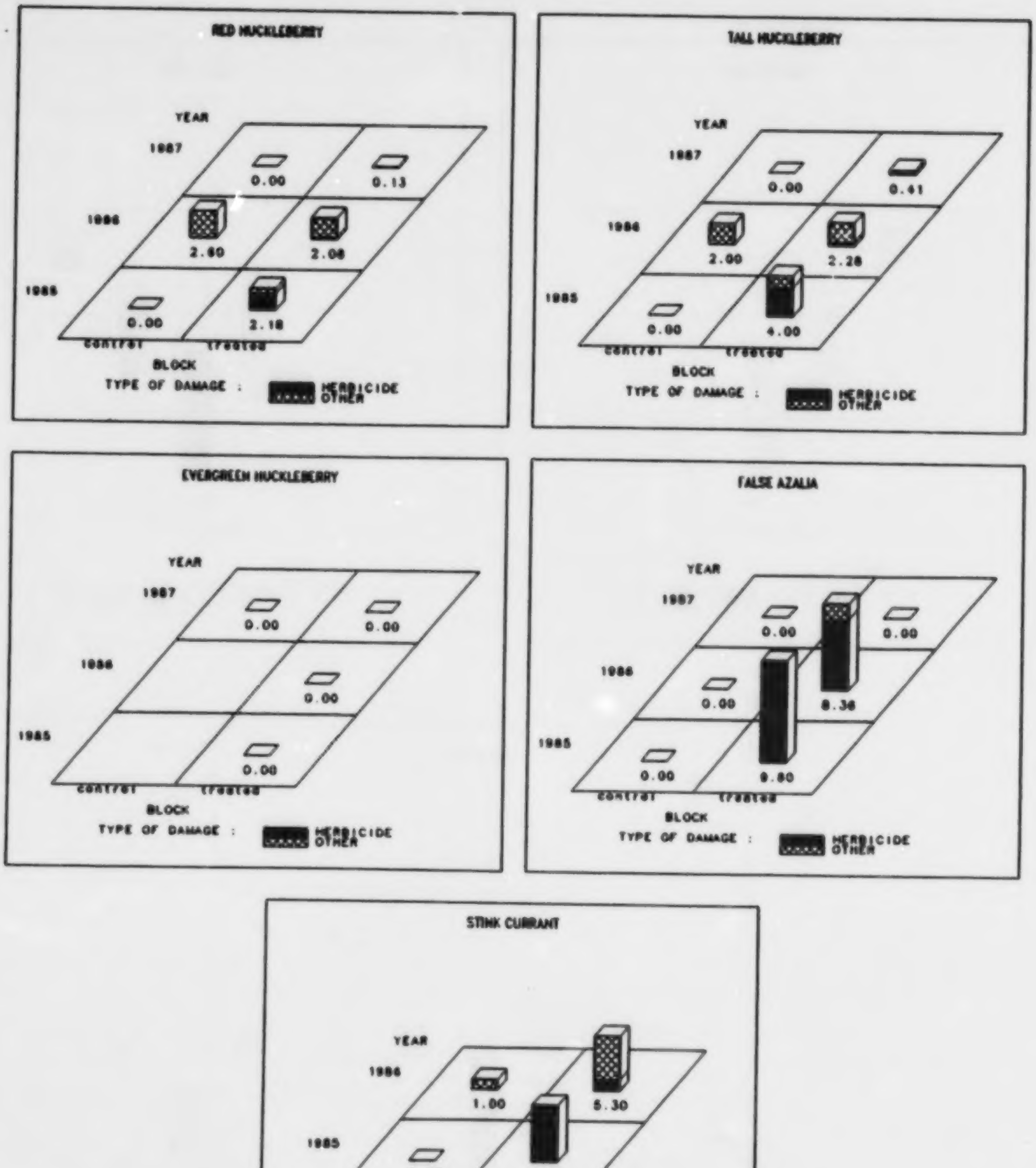


Figure 3. Mean health values for shrubs in the floodplain, by species and year of assessment.

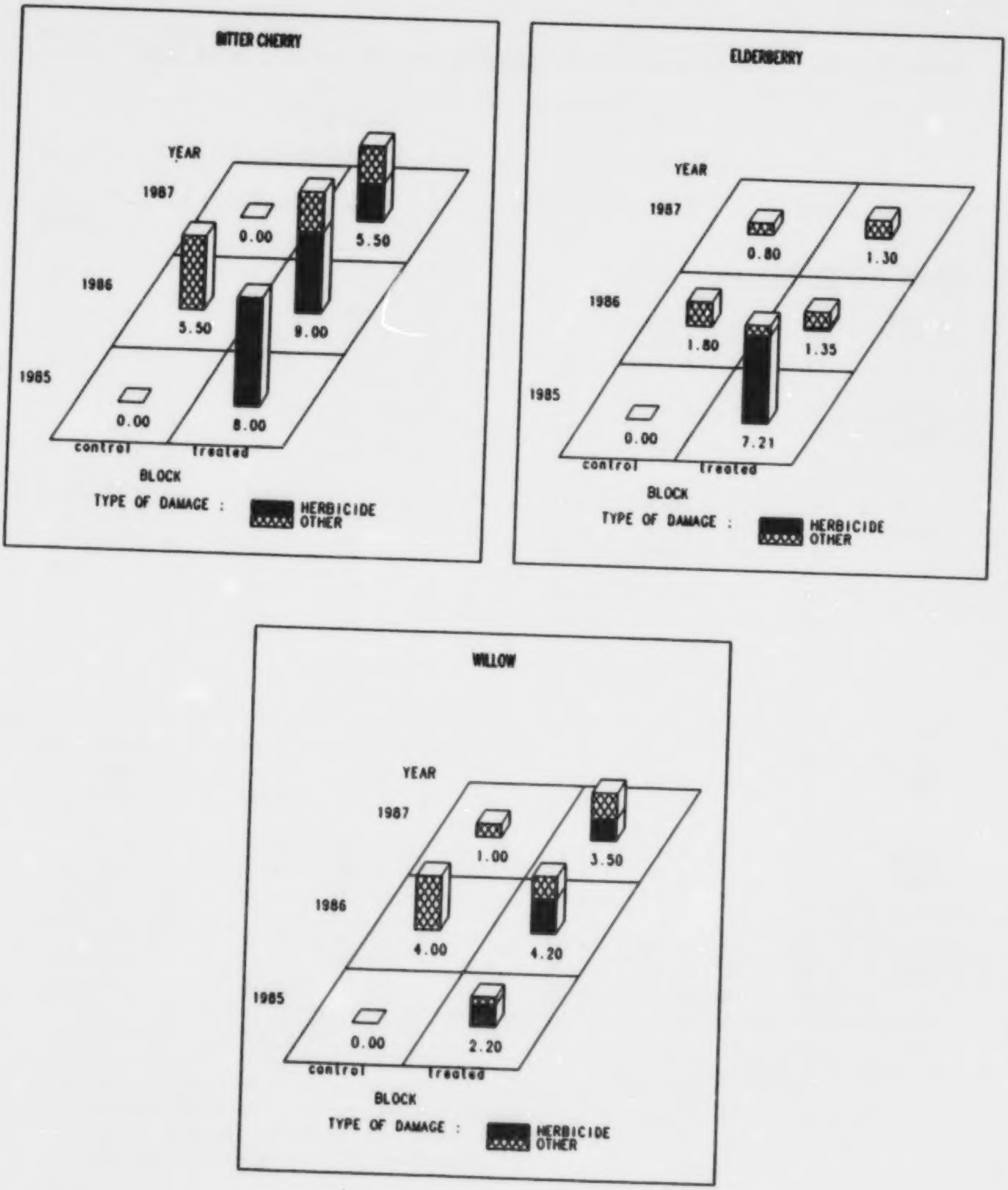


Figure 4. Mean health values for small trees in the floodplain, by species and year of assessment.

Table 1. Herbicide efficacy statistics for treated and untreated weed species

| | | TREATED (floodplain) | | | | CONTROL (floodplain) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Species | Year | n | Mean | Std. Err. | | n | Mean | Std. Err. | (Pr > t) |
| **MAJOR COMPETITORS :** | | | | | | | | | |
| ALDER | 85 | 26 | 6.23 | 0.40 | > | 5 | 0.00 | 0.00 | 0.0001 |
| | 86 | 27 | 3.78 | 0.54 | > | 5 | 1.00 | 0.00 | 0.0001 |
| | 87 | 24 | 3.17 | 0.60 | > | 4 | 0.00 | 0.00 | 0.0001 |
| SALMON-BERRY | 85 | 27 | 8.41 | 0.20 | > | 5 | 0.00 | 0.00 | 0.0001 |
| | 86 | 27 | 4.37 | 0.72 | > | 5 | 1.20 | 0.20 | 0.0710 |
| | 87 | 27 | 5.04 | 0.62 | > | 5 | 0.00 | 0.00 | 0.0017 |
| THIMBLE-BERRY | 85 | 12 | 4.75 | 0.82 | > | 5 | 0.00 | 0.00 | 0.0001 |
| | 86 | 15 | 1.47 | 0.62 | = | 5 | 0.60 | 0.24 | 0.2084 |
| | 87 | 13 | 0.46 | 0.24 | > | 5 | 0.00 | 0.00 | 0.0821 |
| SALAL | 85 | 19 | 0.00 | 0.00 | = | 5 | 0.00 | 0.00 | 1.0000 |
| | 86 | 21 | 0.95 | 0.47 | > | 5 | 0.00 | 0.00 | 0.0541 |
| | 87 | 20 | 0.05 | 0.05 | = | 3 | 0.00 | 0.00 | 0.3299 |
| **FERNS :** | | | | | | | | | |
| SWORD-FERN | 85 | 25 | 3.96 | 0.43 | > | 5 | 0.00 | 0.00 | 0.0001 |
| | 86 | 26 | 0.04 | 0.04 | = | 5 | 0.00 | 0.00 | 0.3269 |
| | 87 | 25 | 0.00 | 0.00 | = | 5 | 0.00 | 0.00 | 1.0000 |
| DEER-FERN | 85 | 27 | 8.70 | 0.40 | > | 5 | 0.00 | 0.00 | 0.0001 |
| | 86 | 27 | 6.00 | 0.92 | > | 5 | 0.00 | 0.00 | 0.0001 |
| | 87 | 17 | 1.47 | 0.83 | > | 5 | 0.00 | 0.00 | 0.0962 |
| LADY-FERN | 85 | 17 | 7.94 | 0.89 | > | 5 | 0.00 | 0.00 | 0.0001 |
| | 86 | 18 | 1.11 | 0.76 | = | 5 | 3.20 | 1.83 | 0.2394 |
| | 87 | 19 | 0.53 | 0.53 | = | 4 | 0.00 | 0.00 | 0.3306 |

...Cont'd.

Table 1. Cont'd.

| | | TREATED (floodplain) | | | | CONTROL (floodplain) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Species | Year | n | Mean | Std. Err. | | n | Mean | Std. Err. | (Pr > t) |
| **SHRUBS :** | | | | | | | | | |
| RED | 85 | 22 | 2.18 | 0.60 | > | 5 | 0.00 | 0.00 | 0.0015 |
| HUCKLE- | 86 | 24 | 2.08 | 0.54 | = | 5 | 2.60 | 1.86 | 0.7210 |
| BERRY | 87 | 23 | 0.13 | 0.10 | = | 3 | 0.00 | 0.00 | 0.1855 |
| TALL | 85 | 14 | 4.00 | 0.86 | ? | 1 | 0.00 | . | . |
| HUCKLE- | 86 | 18 | 2.28 | 0.54 | = | 2 | 2.00 | 1.00 | 0.8692 |
| BERRY | 87 | 17 | 0.41 | 0.30 | = | 2 | 0.00 | 0.00 | 0.1857 |
| EVERGREEN | 85 | 2 | 0.00 | 0.00 | ? | 0 | . | . | . |
| HUCKLE- | 86 | 4 | 0.00 | 0.00 | ? | 0 | . | . | . |
| BERRY | 87 | 5 | 0.00 | 0.00 | ? | 1 | 0.00 | . | . |
| FALSE | 85 | 10 | 9.80 | 0.13 | ? | 1 | 0.00 | . | . |
| AZALIA | 86 | 11 | 8.36 | 0.97 | ? | 1 | 0.00 | . | . |
| | 87 | 2 | 0.00 | 0.00 | ? | 1 | 0.00 | . | . |
| STINK | 85 | 4 | 5.50 | 2.63 | ? | 1 | 0.00 | . | . |
| CURRANT | 86 | 6 | 5.30 | 2.09 | ? | 1 | 1.00 | . | . |
| | 87 | 0 | . | . | . | 0 | . | . | . |
| **SMALL TREES :** | | | | | | | | | |
| BITTER | 85 | 6 | 8.00 | 1.13 | > | 2 | 0.00 | 0.00 | 0.0009 |
| CHERRY | 86 | 6 | 9.00 | 0.68 | = | 2 | 5.50 | 4.50 | 0.5799 |
| | 87 | 2 | 5.50 | 4.50 | ? | 1 | 0.00 | . | . |
| ELDER- | 85 | 19 | 7.21 | 0.54 | > | 3 | 0.00 | 0.00 | 0.0001 |
| BERRY | 86 | 23 | 1.35 | 0.26 | = | 5 | 1.80 | 0.37 | 0.4433 |
| | 87 | 20 | 1.30 | 0.30 | = | 5 | 0.80 | 0.20 | 0.1805 |
| WILLOW | 85 | 5 | 2.20 | 1.24 | = | 2 | 0.00 | 0.00 | 0.1509 |
| | 86 | 5 | 4.20 | 1.39 | = | 3 | 4.00 | 3.00 | 0.9467 |
| | 87 | 2 | 3.50 | 1.50 | ? | 1 | 1.00 | . | . |

Note: All values are health ratings (0 = healthy, 10 = dead). Treated and untreated means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair.

Table 2. Weed species that show differences between lower-slope and floodplain health values, after herbicide treatment

| | | TREATED | | | | CONTROL (floodplain) |
|---|---|---|---|---|---|---|
| SPECIES | YEAR | LOWER-SLOPE | | FLOODPLAIN | (Pr > t) | |
| ALDER | 85 | 7.90 | > | 6.23 | 0.0301 | 0.00 |
| | 86 | 5.75 | > | 3.78 | 0.0721 | 1.00 |
| | 87 | 4.91 | = | 3.17 | 0.1625 | 0.00 |
| SWORD-FERN | 85 | 5.22 | > | 3.96 | 0.0595 | 0.00 |
| | 86 | 1.11 | = | 0.04 | 0.3628 | 0.00 |
| | 87 | 0.00 | = | 0.00 | 1.0000 | 0.00 |
| THIMBLE-BERRY | 85 | 8.00 | > | 4.75 | 0.0429 | 0.00 |
| | 86 | 4.57 | = | 1.47 | 0.1671 | 0.60 |
| | 87 | 0.00 | = | 0.46 | 0.4836 | 0.00 |

Note: All values are HEALTH ratings (0 = healthy, 10 = dead). Upland and lowland means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair. Treatment means that differ from the control means, at the 95% level, are underlined.

Table 3. Crop-tolerance statistics for treated and untreated crop species

| | | TREATED (floodplain) | | | | CONTROL (floodplain) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Species | Year | n | Mean | Std. Err. | | n | Mean | Std. Err. | (Pr > t) |
| SITKA SPRUCE | 85 | 26 | 0.0 | 0.0 | = | 5 | 0.2 | 0.2 | 0.3739 |
| | 86 | 27 | 0.4 | 0.1 | = | 5 | 0.8 | 0.4 | 0.1992 |
| | 87 | 25 | 0.0 | 0.0 | = | 6 | 0.0 | 0.0 | 0.3273 |
| WESTERN HEMLOCK | 85 | 23 | 0.8 | 0.1 | > | 4 | 0.0 | 0.0 | 0.0001 |
| | 86 | 23 | 0.4 | 0.4 | = | 4 | 0.0 | 0.0 | 0.3282 |
| | 87 | 20 | 0.0 | 0.0 | = | 4 | 0.0 | 0.0 | 1.0000 |
| WESTERN REDCEDAR | 85 | 25 | 0.3 | 0.1 | > | 5 | 0.0 | 0.0 | 0.0026 |
| | 86 | 24 | 0.0 | 0.0 | = | 5 | 0.2 | 0.2 | 0.4787 |
| | 87 | 24 | 0.0 | 0.0 | = | 5 | 0.0 | 0.0 | 1.0000 |

Note: All values are health ratings (0 = healthy, 10 = dead). Treated and untreated means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair.

## Crop Tolerance

Some minor crop tree injury resulted following glyphosate treatment for western hemlock and to a lesser extent for western red cedar (Fig. 5). Initial injury consisted of dieback of the primary leader and was not observed for other crop trees (i.e., sitka spruce, amabilis fir and Douglas-fir). Initial herbicide injury of hemlock and cedar disappeared in 1986 and 1987. A statistical analysis of this injury is presented in Table 3, and confirms that hemlock and cedar injury was statistically significant in 1985, but was not significant in 1986 or 1987.

## Crop Growth

Growth of sitka spruce, prior to and after glyphosate treatment, is presented in Figure 6. Height and height increment of spruce was greater prior to glyphosate treatment for trees sprayed with glyphosate than for those not treated with the herbicide. Following treatment, height growth remained greater for treated trees in 1985, 1986 and 1987; height increment remained greater for treated trees in 1985, but declined within the standard error for untreated trees in 1986 and 1987. Diameter growth of spruce was approximately the same or slightly higher prior to glyphosate treatment for trees sprayed with glyphosate as compared with those not treated with the herbicide. Following treatment, diameter growth was greater for treated trees in 1985, 1986 and 1987; diameter increment for treated and control trees overlapped in 1985, but was greater for treated trees in 1986 and 1987.

Table 4 confirms that treated and control spruce trees differed significantly in height and height-increment in 1984 prior to glyphosate treatment. However, root-collar diameter for treated spruce was not significantly different from that for control spruce prior to glyphosate treatment. Following treatment, diameter growth was significantly greater for treated trees in 1985, 1986 and 1987; diameter increment was significantly greater for treated trees in 1986 and 1987.

Table 5 further confirms that spruce growth (i.e., height-increment) was not the same for floodplain and lower slope microsites prior to glyphosate treatment. For this reason, and also due to a complete lack of lower slope controls, lower slope spruce data has been eliminated from consideration or presentation in Figure 6 or Table 4.

Growth measurements for hemlock and cedar are fewer in number than those reported for spruce, and the reliability of such measurements is less than that for spruce because of uncertainties associated with accurately measuring internodal growth. However, despite these pitfalls, statistical and otherwise, the data we have are presented here for sake of completeness and because trends evident in the spruce data are confirmed by the existing hemlock and cedar data.

Growth of hemlock is presented in Figure 7. Prior to glyphosate treatment, hemlock height and height-increment for treated trees was equal to or less than that for control trees. Following treatment hemlock root-collar diameter was approximately equal in 1985 for treated and control trees, but was greater for treated trees in 1986. Hemlock root-collar diameter increment was greater for treated trees in 1986 and overlapped with control trees in 1987.

Table 6 confirms that there were no statistically significant differences in growth for hemlock prior to glyphosate treatment. Following glyphosate treatment, hemlock diameter increment was significantly greater in 1986 for treated trees. Table 7 confirms that 1983 hemlock height growth was greater for trees growing on lower slope microsites.

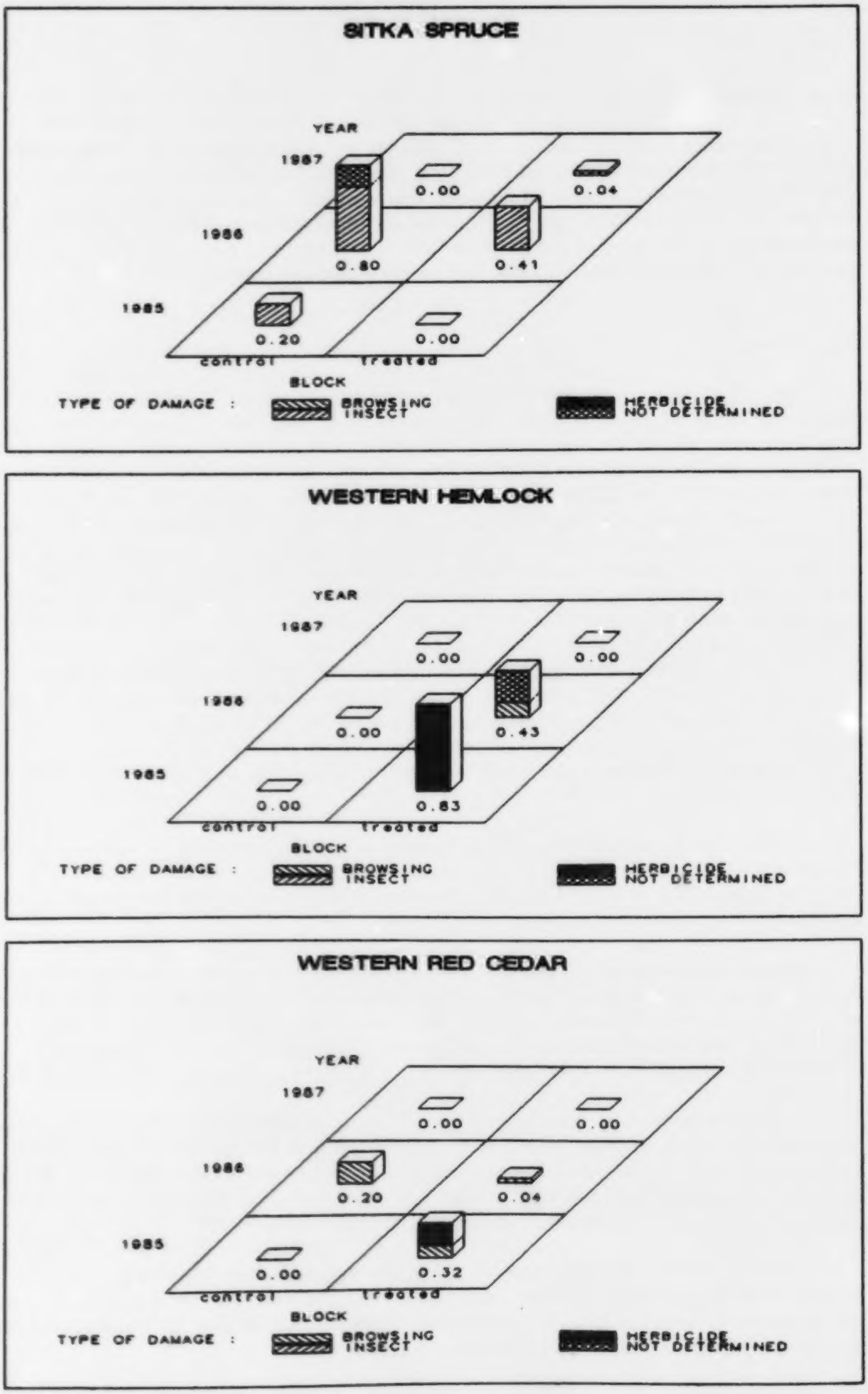
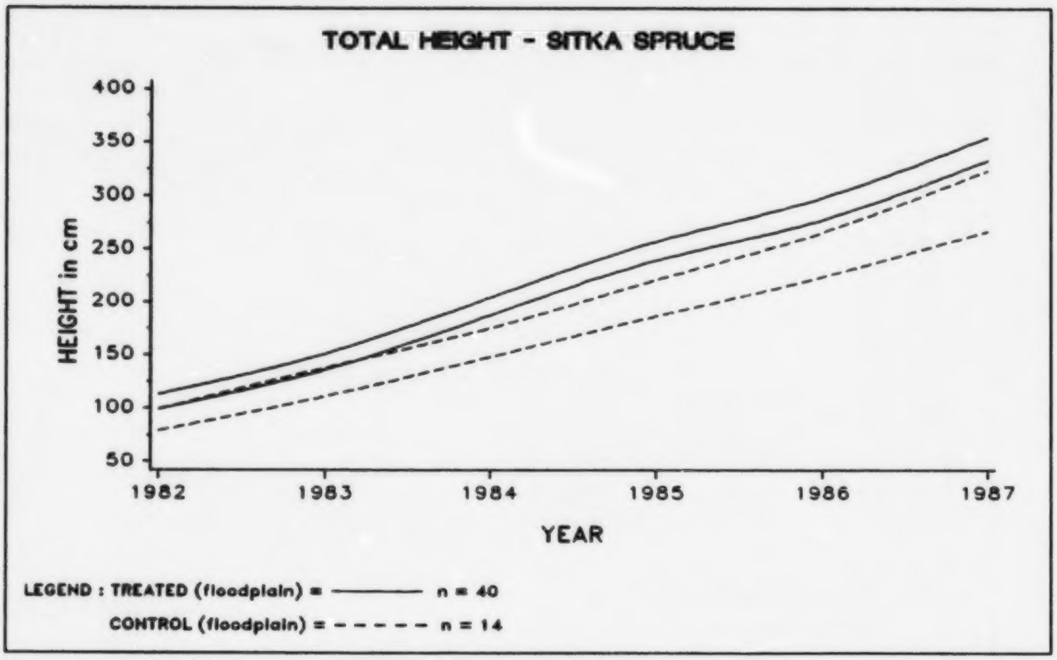


Figure 5. Mean crop-tolerance values for crop trees in the floodplain, by species and year of assessment.



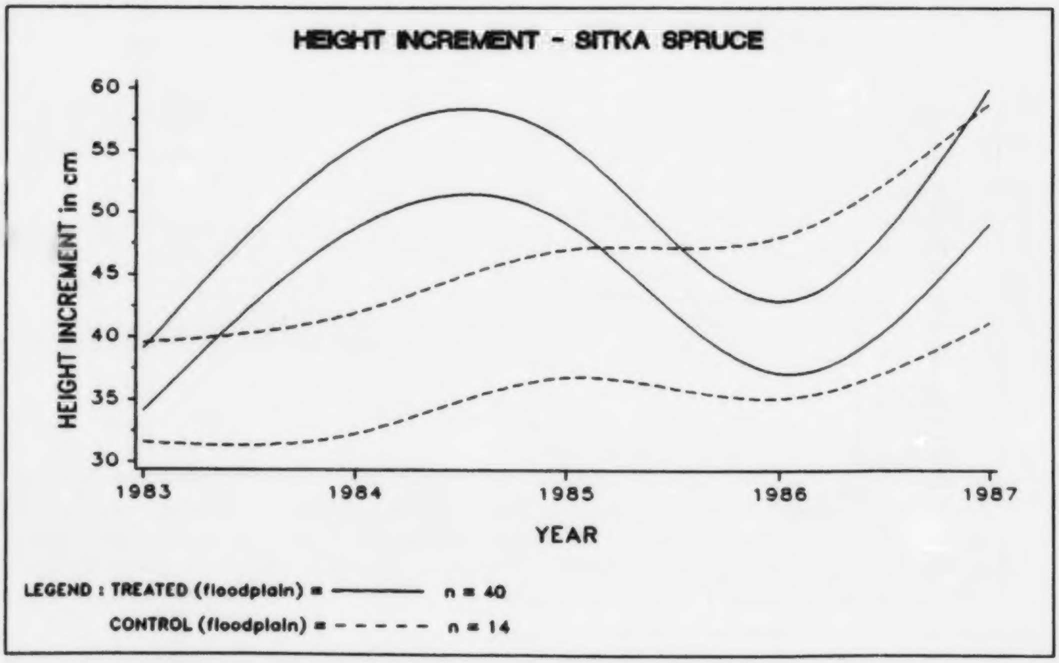


**Figure 6a.** Mean height and height increment, + and - their standard errors, for sitka spruce.

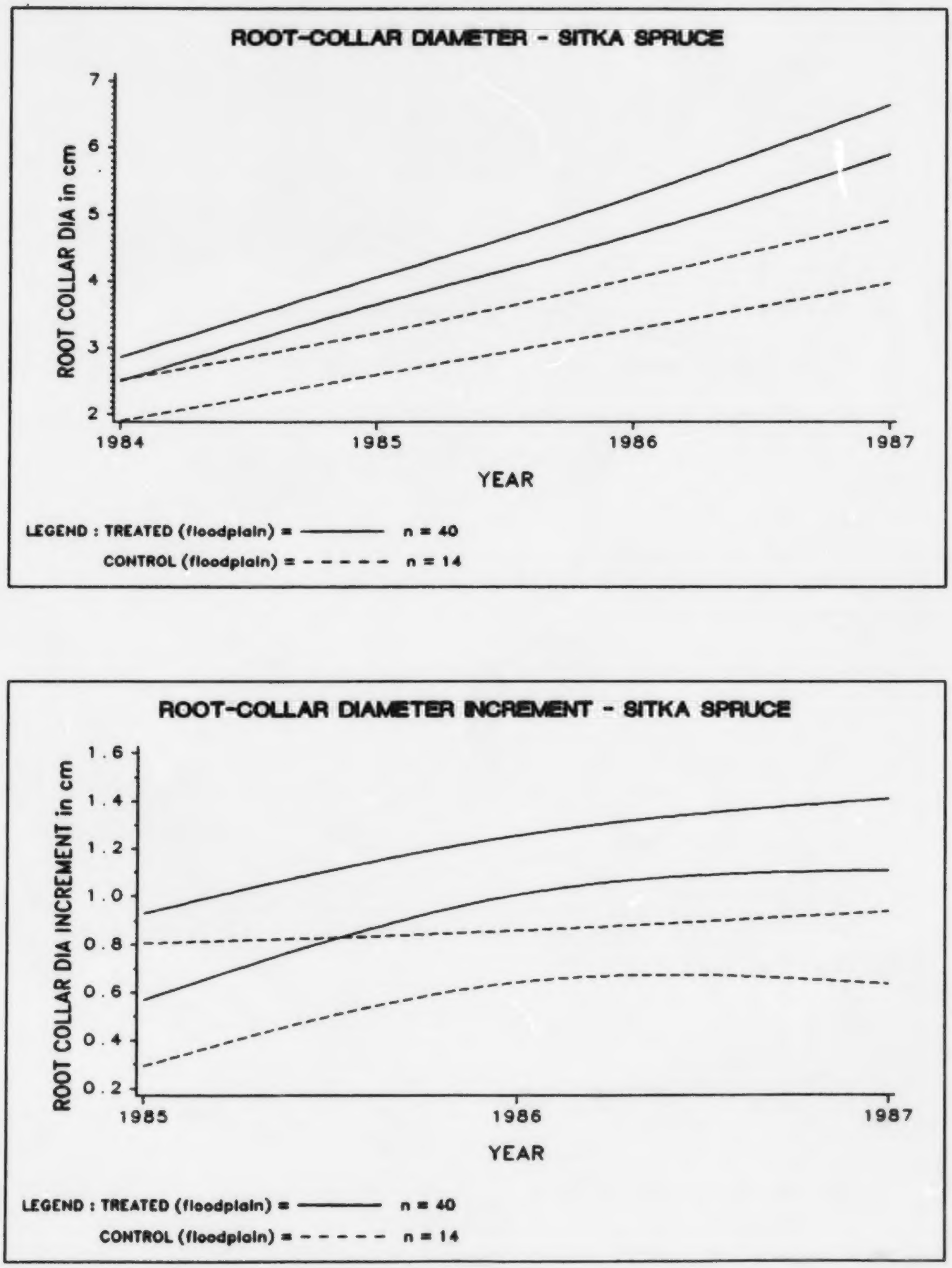


**Figure 6b.** Mean root-collar diameter and root-collar diameter increment, + and - their standard errors, for sitka spruce.

Table 4. Crop growth response statistics for treated and untreated Sitka spruce

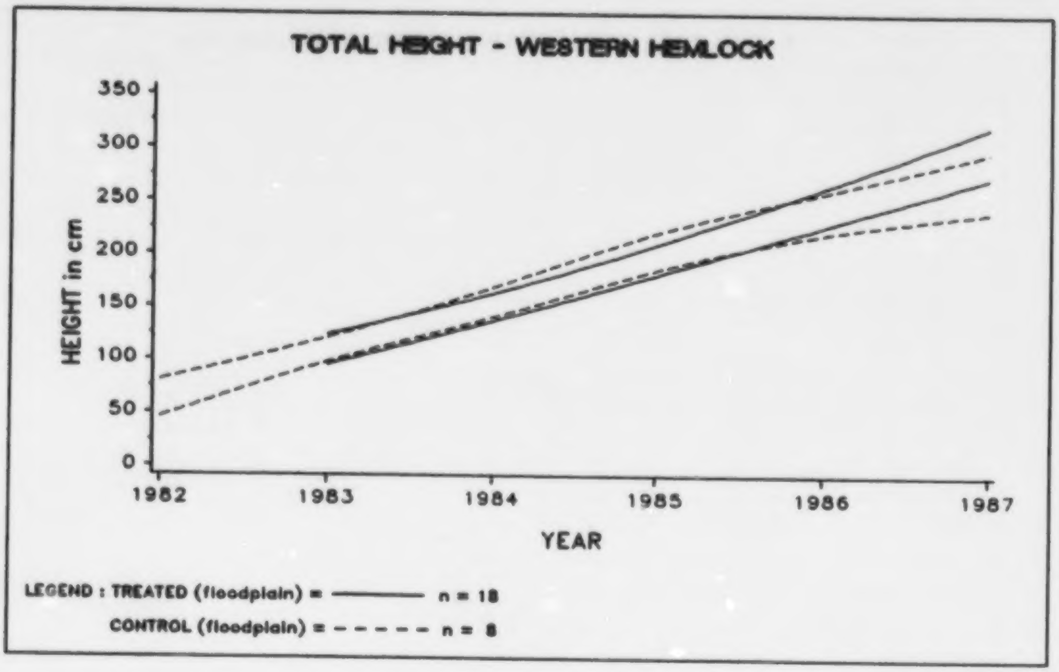
| | TREATED (Floodplain) | | | | CONTROL (Floodplain) | | | |
|---|---|---|---|---|---|---|---|---|
| Measure | N | Mean | Std. Err. | | N | Mean | Std. Err. | (Pr > T) |
| **HEIGHT :** | | | | | | | | |
| 1982 | 38 | 106.1 | 6.8 | = | 14 | 89.0 | 10.0 | 0.1876 |
| 1983 | 40 | 143.7 | 7.6 | = | 14 | 124.6 | 13.5 | 0.2116 |
| 1984 | 40 | 195.8 | 8.3 | > | 14 | 161.7 | 13.5 | 0.0391 |
| 1985 | 40 | 248.2 | 8.9 | > | 14 | 203.6 | 17.2 | 0.0176 |
| 1986 | 40 | 288.3 | 10.3 | > | 14 | 245.2 | 21.0 | 0.0486 |
| 1987 | 39 | 343.9 | 10.6 | > | 14 | 295.2 | 28.3 | 0.1257 |
| **HEIGHT INCREMENT :** | | | | | | | | |
| 1983 | 38 | 36.6 | 2.5 | = | 14 | 35.6 | 4.0 | 0.8296 |
| 1984 | 40 | 52.1 | 3.3 | > | 14 | 37.1 | 4.9 | 0.0221 |
| 1985 | 40 | 52.4 | 3.3 | > | 14 | 41.9 | 5.1 | 0.1020 |
| 1986 | 40 | 40.1 | 2.9 | = | 14 | 41.6 | 6.4 | 0.8052 |
| 1987 | 39 | 54.5 | 5.4 | = | 14 | 50.0 | 8.8 | 0.6678 |
| **ROOT-COLLAR DIAMETER :** | | | | | | | | |
| 1984 | 14 | 2.7 | 0.2 | = | 8 | 2.2 | 0.3 | 0.1724 |
| 1985 | 40 | 3.9 | 0.2 | > | 14 | 2.9 | 0.3 | 0.0191 |
| 1986 | 40 | 5.0 | 0.3 | > | 14 | 3.7 | 0.4 | 0.0172 |
| 1987 | 39 | 6.3 | 0.4 | > | 14 | 4.5 | 0.5 | 0.0103 |
| **ROOT-COLLAR DIAMETER INCREMENT :** | | | | | | | | |
| 1985 | 14 | 0.8 | 0.2 | = | 8 | 0.6 | 0.3 | 0.5221 |
| 1986 | 40 | 1.1 | 0.1 | > | 14 | 0.8 | 0.1 | 0.0265 |
| 1987 | 39 | 1.3 | 0.2 | > | 14 | 0.8 | 0.2 | 0.0327 |

Note: All measurements are in cm. Treated and untreated means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair.

Table 5. Comparison of lower-slope and floodplain growth measurements for Sitka spruce

| | TREATED | | | | CONTROL (floodplain) |
|---|---|---|---|---|---|
| MEASURE | LOWER SLOPE | | FLOODPLAIN | (Pr > t) | |
| n | 8 | | 40 | | 14 |
| HEIGHT : | | | | | |
| 1982 | 105.8 | = | 106.1 | 0.9846 | 89.0 |
| 1983 | 136.1 | = | 143.7 | 0.8185 | 124.6 |
| 1984 | 172.9 | = | 195.8 | 0.5406 | 161.7 |
| 1985 | 213.5 | = | 248.2 | 0.3842 | 203.6 |
| 1986 | 250.1 | = | 288.3 | 0.3384 | 245.2 |
| 1987 | 301.6 | = | 343.9 | 0.1340 | 295.2 |
| HEIGHT INCREMENT : | | | | | |
| 1983 | 30.4 | = | 36.6 | 0.3044 | 35.6 |
| 1984 | 36.8 | < | 52.1 | 0.0606 | 37.1 |
| 1985 | 40.6 | < | 52.4 | 0.0378 | 41.9 |
| 1986 | 36.6 | = | 40.1 | 0.4379 | 41.6 |
| 1987 | 51.5 | = | 54.5 | 0.8126 | 50.0 |
| ROOT-COLLAR DIAMETER : | | | | | |
| 1984 | . | ? | 2.7 | . | 2.2 |
| 1985 | 3.8 | = | 3.9 | 0.9430 | 2.9 |
| 1986 | 4.4 | = | 5.0 | 0.4347 | 3.7 |
| 1987 | 5.3 | = | 6.3 | 0.2858 | 4.5 |
| ROOT-COLLAR DIAMETER INCREMENT : | | | | | |
| 1985 | . | ? | 0.8 | . | 0.6 |
| 1986 | 1.0 | = | 1.1 | 0.7513 | 0.8 |
| 1987 | 0.7 | < | 1.3 | 0.0256 | 0.8 |

Note: All measurements are in cm. Upland and lowland means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair. Treatment means that differ from the control means, at the 95 % level, are underlined.



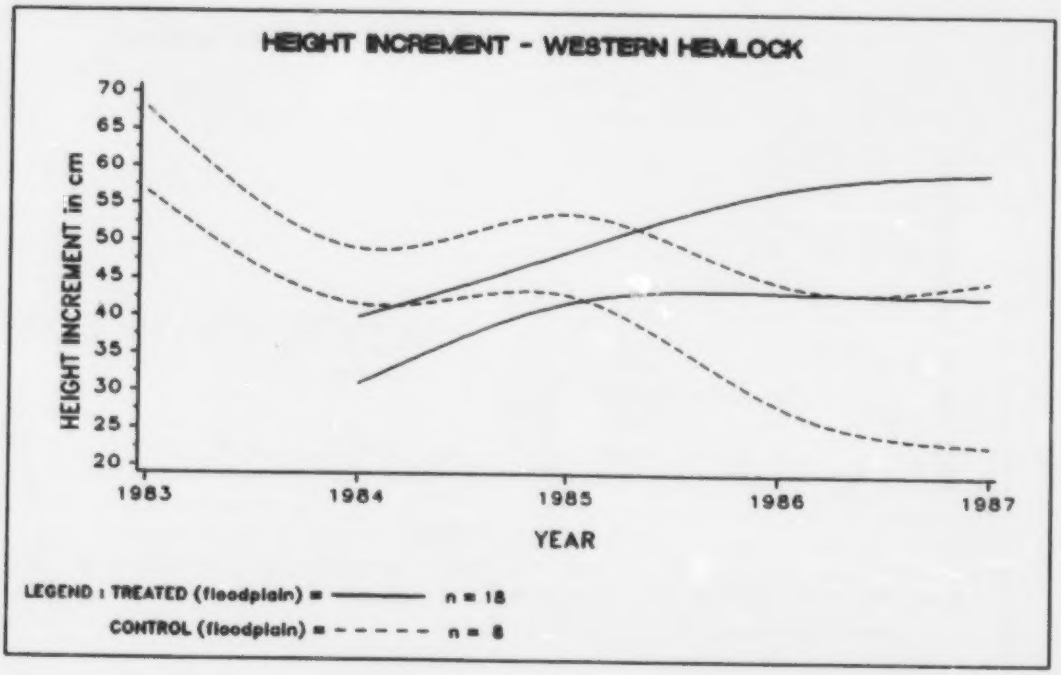


**Figure 7a.** Mean height and height increment, + and - their standard errors, for western hemlock.

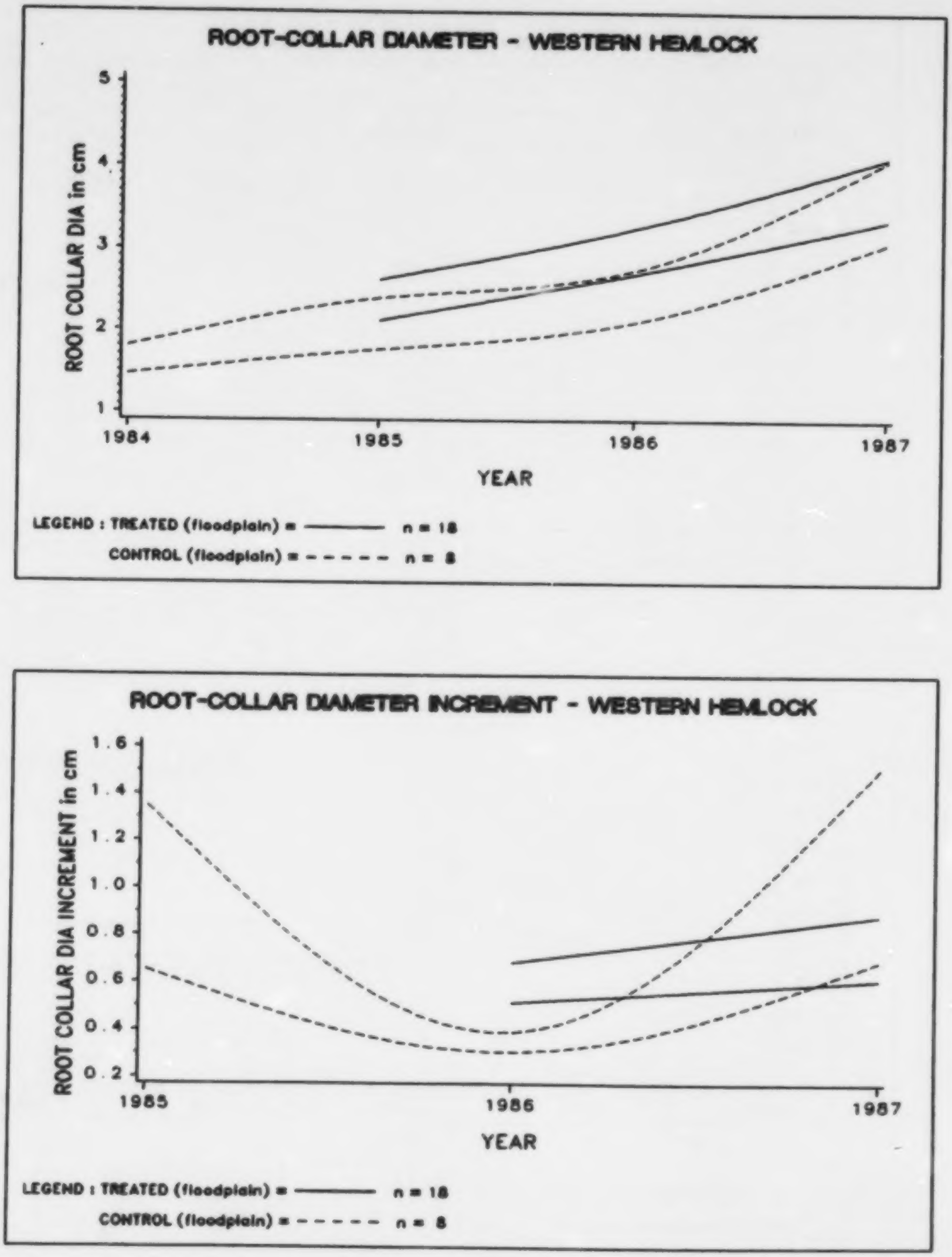


Figure 7b. Mean root-collar diameter and root-collar diameter increment, + and - their standard errors, for western hemlock.

Table 6. Crop growth response statistics for treated and untreated western hemlock

| | TREATED (floodplain) | | | | CONTROL (floodplain) | | | |
|---|---|---|---|---|---|---|---|---|
| Measure | n | Mean | Std. Err. | | n | Mean | Std. Err. | (Pr > t) |
| **HEIGHT :** | | | | | | | | |
| 1982 | 0 | . | . | ? | 4 | 63.0 | 17.5 | . |
| 1983 | 15 | 109.3 | 14.2 | = | 8 | 109.3 | 11.4 | 0.9969 |
| 1984 | 18 | 149.9 | 13.0 | = | 8 | 154.6 | 14.1 | 0.8313 |
| 1985 | 18 | 195.2 | 14.3 | = | 8 | 203.0 | 17.4 | 0.7533 |
| 1986 | 18 | 245.4 | 18.1 | = | 8 | 239.5 | 19.7 | 0.8458 |
| 1987 | 18 | 296.7 | 23.6 | = | 7 | 268.9 | 28.0 | 0.5131 |
| **HEIGHT INCREMENT :** | | | | | | | | |
| 1983 | 0 | . | . | ? | 4 | 62.3 | 5.6 | . |
| 1984 | 15 | 35.5 | 4.4 | = | 8 | 45.4 | 3.7 | 0.1543 |
| 1985 | 18 | 45.3 | 3.4 | = | 8 | 48.4 | 5.4 | 0.6246 |
| 1986 | 18 | 50.2 | 6.8 | = | 8 | 36.5 | 8.2 | 0.2465 |
| 1987 | 18 | 51.2 | 8.3 | = | 7 | 34.1 | 11.0 | 0.2661 |
| **ROOT-COLLAR DIAMETER :** | | | | | | | | |
| 1984 | 0 | . | . | ? | 4 | 1.6 | 0.2 | . |
| 1985 | 18 | 2.4 | 0.3 | = | 8 | 2.1 | 0.3 | 0.4996 |
| 1986 | 18 | 3.0 | 0.3 | = | 8 | 2.4 | 0.3 | 0.2543 |
| 1987 | 18 | 3.7 | 0.4 | = | 7 | 3.6 | 0.5 | 0.8289 |
| **ROOT-COLLAR DIAMETER INCREMENT :** | | | | | | | | |
| 1985 | 0 | . | . | ? | 4 | 1.0 | 0.3 | . |
| 1986 | 18 | 0.6 | 0.1 | > | 8 | 0.4 | 0.1 | 0.0134 |
| 1987 | 18 | 0.8 | 0.1 | = | 7 | 1.1 | 0.4 | 0.4422 |

Note: All measurements are in cm. Treated and untreated means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair.

Table 7. Comparison of lower-slope and floodplain growth measurements for western hemlock

| | TREATED | | | | CONTROL |
|---|---|---|---|---|---|
| MEASURE | LOWER SLOPE | | FLOODPLAIN | (Pr > t) | (floodplain) |
| n | 14 | | 18 | | 8 |
| HEIGHT : | | | | | |
| 1982 | 93.3 | ? | . | . | 63.0 |
| 1983 | 155.7 | > | 109.3 | 0.0508 | 109.3 |
| 1984 | 181.4 | = | 149.9 | 0.1645 | 154.6 |
| 1985 | 220.0 | = | 195.2 | 0.3049 | 203.0 |
| 1986 | 260.4 | = | 245.4 | 0.6034 | 239.5 |
| 1987 | 312.3 | = | 296.7 | 0.6407 | 268.9 |
| HEIGHT INCREMENT : | | | | | |
| 1983 | 59.8 | ? | . | . | 62.3 |
| 1984 | 31.8 | = | 35.5 | 0.5533 | 45.4 |
| 1985 | 38.6 | = | 45.3 | 0.2486 | 48.4 |
| 1986 | 40.4 | = | 50.2 | 0.3464 | 36.5 |
| 1987 | 51.9 | = | 51.2 | 0.9616 | 34.1 |
| ROOT-COLLAR DIAMETER : | | | | | |
| 1984 | 2.0 | ? | . | . | 1.6 |
| 1985 | 2.9 | = | 2.4 | 0.1999 | 2.1 |
| 1986 | 3.4 | = | 3.0 | 0.3213 | 2.4 |
| 1987 | 3.9 | = | 3.7 | 0.7511 | 3.6 |
| ROOT-COLLAR DIAMETER INCREMENT : | | | | | |
| 1985 | 0.4 | ? | . | . | 1.0 |
| 1986 | 0.5 | = | 0.6 | 0.6024 | 0.4 |
| 1987 | 0.5 | = | 0.8 | 0.1491 | 1.1 |

Note: All measurements are in cm. Upland and Lowland means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair. Treatment means that differ from the control means, at the 95% level, are underlined.

Growth of cedar is presented in Figure 8. Prior to and after glyphosate treatment, cedar height and height-increment growth for treated trees overlapped with that for control trees. Following herbicide treatment, cedar diameter growth for treated trees overlapped with that for control trees. However, cedar diameter increment was greater in 1987 for treated trees.

Table 8 confirms that there were no statistically significant differences in growth for cedar prior to or after glyphosate treatment. Table 9 confirms that 1987 cedar diameter increment was significantly greater for floodplain trees as compared with that for cedar trees growing on lower slope microsites.

## DISCUSSION

The present study confirms that glyphosate provided satisfactory control of weed competitors for one growing season following herbicide treatment. Progressive decline of herbicide efficacy in 1986 and 1987 is reasonable considering the initial size (i.e., above-ground biomass and below-ground root mass) of the two major weed competitors. Alder growth equal to or greater than 15 meters and salmonberry thickets approaching 4 meters height, prior to glyphosate treatment, were not uncommon. Maximum herbicide efficacy is attained when brush competition is young and not well established. Preferably, herbicide treatment should occur within one year of logging for highly productive coastal sites. If treatment is delayed, the below-ground root mass becomes well-established and difficult to kill. Under such circumstances, control often appears high for one year after treatment, but declines thereafter. Logging of Carnation Creek began in 1975 and continued through 1981, the most recent being three years prior to herbicide treatment. Because of the advanced brush condition, it is concluded that the herbicide treatment controlled the brush better than expected, and that the lack of prolonged control was neither the fault of the herbicide chosen nor the delivery system employed.

The inability of glyphosate to control certain species (e.g., salal or evergreen huckleberry) confirms that all species will not be eliminated by judicious herbicide use. Many of these species do not constitute serious weed competitors, and are important components of wildlife or fish habitat.

Broader spectrum weed control, even for important competitors (e.g., alder, salmonberry, thimbleberry and salal), will require much earlier use of existing herbicides in the harvest-forest renewal cycle and may necessitate the use of newer broader-spectrum herbicides offering better control of weeds presently controlled by glyphosate or control of weeds, such as salal, not controlled by glyphosate.

Improved herbicide efficacy may also be achieved by using smaller droplet delivery systems coupled with ultra-low carrier volumes. However, improved application technology may have to be foregone for the sake of reducing aerial drift and protecting riparian habitat. In the present study, the MICROFOIL BOOM, was chosen primarily for this purpose. It is likely that large droplet, high volume systems, such as the MICROFOIL, are a necessity for advanced brush conditions (i.e., multiple weed canopies, tree, shrub, herb) if multiple herbicide applications are to be avoided. It is unlikely that small droplet, low volume systems would provide sufficient canopy penetration to preclude multiple herbicide applications where advanced brush conditions have been allowed to develop unabated. Hence, improved efficacy may be a tradeoff where environmental concerns (e.g., drift, protection of riparian habitat, multiple herbicide applications on the same site) are of paramount importance.

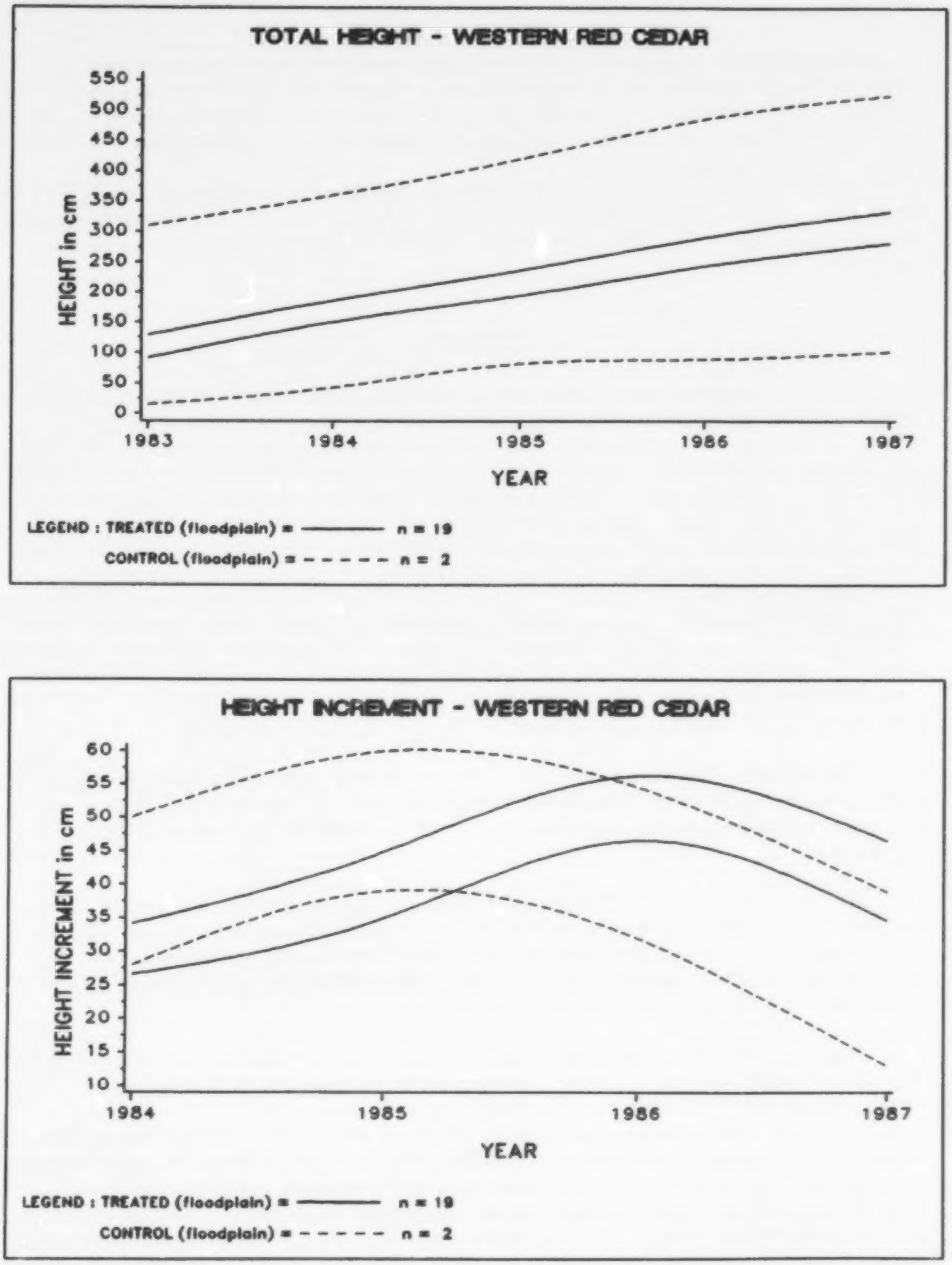


Figure 8a. Mean height and height increment, + and - their standard errors, for western red cedar.

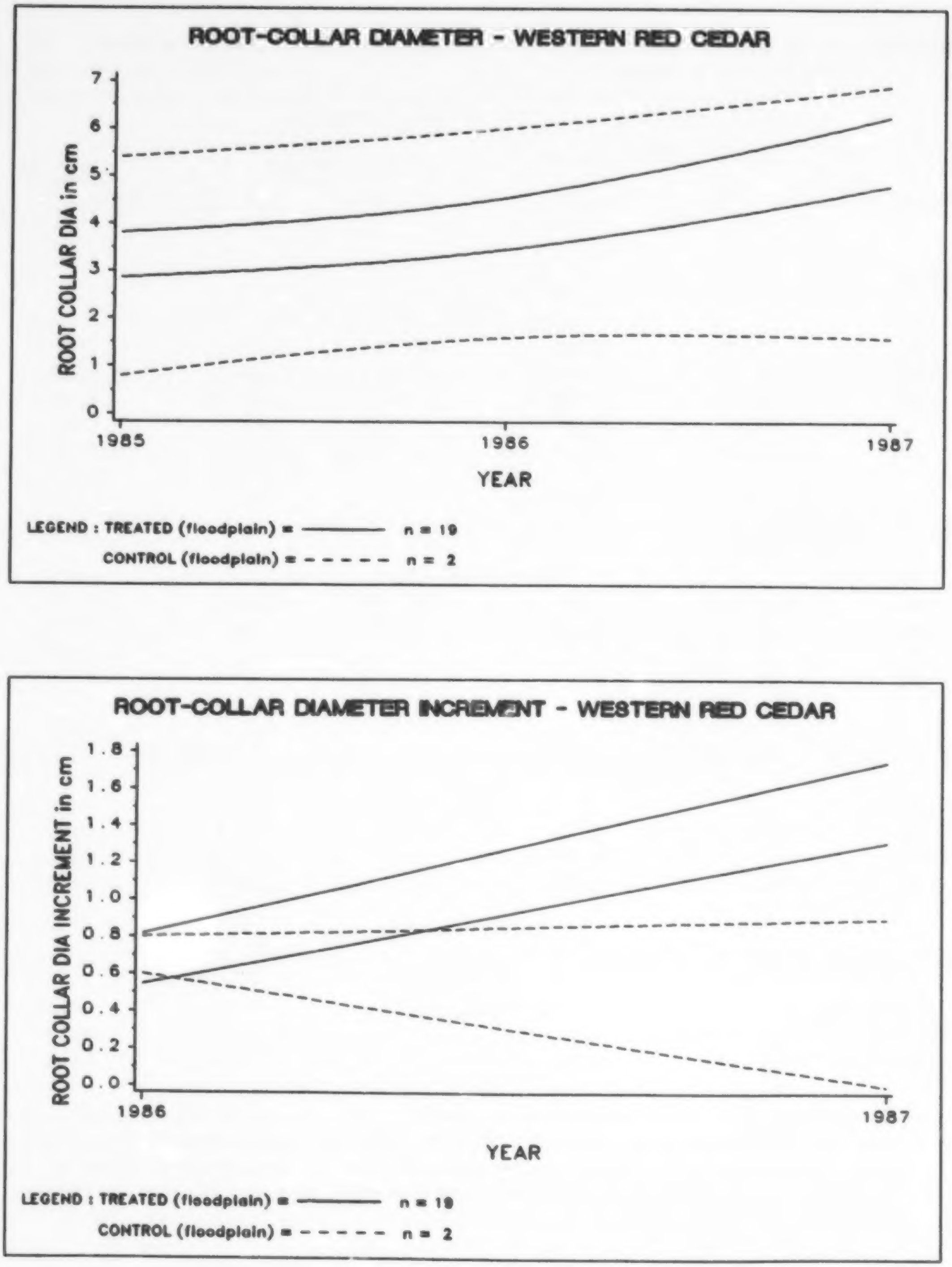


Figure 8b. Mean root-collar diameter and root-collar diameter increment, + and - their standard errors, for western red cedar.

Table 8. Crop growth response statistics for treated and untreated western red cedar

| | TREATED (floodplain) | | | | CONTROL (floodplain) | | | |
|---|---|---|---|---|---|---|---|---|
| Measure | n | Mean | Std. Err. | | n | Mean | Std. Err. | (Pr > t) |
| **HEIGHT :** | | | | | | | | |
| 1982 | | | | not measured | | | | |
| 1983 | 12 | 110.2 | 18.9 | = | 2 | 162.5 | 147.5 | 0.7837 |
| 1984 | 18 | 168.1 | 17.8 | = | 2 | 201.5 | 158.5 | 0.8682 |
| 1985 | 19 | 215.5 | 20.9 | = | 2 | 251.0 | 169.0 | 0.8686 |
| 1986 | 19 | 266.9 | 23.5 | = | 2 | 287.5 | 198.5 | 0.9344 |
| 1987 | 19 | 307.1 | 25.7 | = | 2 | 313.5 | 211.5 | 0.9808 |
| **HEIGHT INCREMENT :** | | | | | | | | |
| 1983 | | | | not measured | | | | |
| 1984 | 12 | 30.3 | 3.8 | = | 2 | 39.0 | 11.0 | 0.4098 |
| 1985 | 18 | 39.9 | 5.0 | = | 2 | 49.5 | 10.5 | 0.5414 |
| 1986 | 19 | 51.4 | 4.9 | = | 2 | 36.5 | 29.5 | 0.3879 |
| 1987 | 19 | 40.2 | 6.1 | = | 2 | 26.0 | 13.0 | 0.4758 |
| **ROOT-COLLAR DIAMETER :** | | | | | | | | |
| 1984 | | | | not measured | | | | |
| 1985 | 19 | 3.3 | 2.3 | = | 2 | 3.1 | 2.3 | 0.8868 |
| 1986 | 19 | 4.0 | 0.5 | = | 2 | 3.8 | 2.2 | 0.9085 |
| 1987 | 19 | 5.5 | 0.7 | = | 2 | 4.3 | 2.7 | 0.5889 |
| **ROOT-COLLAR DIAMETER INCREMENT :** | | | | | | | | |
| 1985 | | | | not measured | | | | |
| 1986 | 19 | 0.7 | 0.1 | = | 2 | 0.7 | 0.1 | 0.9613 |
| 1987 | 19 | 1.5 | 0.2 | = | 2 | 0.5 | 0.5 | 0.1353 |

Note: All measurements are in cm. Treated and untreated means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair.

Table 9. Comparison of lower-slope and floodplain growth measurements for western red cedar.

| | TREATED | | | | CONTROL |
|---|---|---|---|---|---|
| MEASURE | LOWER SLOPE | | FLOODPLAIN | (Pr > t) | (floodplain) |
| n | 7 | | 19 | | 2 |
| **HEIGHT :** | | | | | |
| 1982 | not measured | | | | |
| 1983 | 124.7 | = | 110.2 | 0.6418 | 162.5 |
| 1984 | 152.6 | = | 168.1 | 0.6334 | 201.5 |
| 1985 | 194.9 | = | 215.5 | 0.5924 | 251.0 |
| 1986 | 257.1 | = | 266.9 | 0.8210 | 287.5 |
| 1987 | 321.1 | = | 307.1 | 0.7620 | 313.5 |
| **HEIGHT INCREMENT :** | | | | | |
| 1983 | not measured | | | | |
| 1984 | 27.9 | = | 30.3 | 0.6826 | 39.0 |
| 1985 | 42.3 | = | 39.9 | 0.6895 | 49.5 |
| 1986 | 62.3 | = | 51.4 | 0.2132 | 36.5 |
| 1987 | 64.0 | > | 40.2 | 0.0532 | 26.0 |
| **ROOT-COLLAR DIAMETER :** | | | | | |
| 1984 | not measured | | | | |
| 1985 | 3.8 | = | 3.3 | 0.6529 | 3.1 |
| 1986 | 4.6 | = | 4.0 | 0.5666 | 3.8 |
| 1987 | 5.2 | = | 5.2 | 0.8151 | 4.3 |
| **ROOT-COLLAR DIAMETER INCREMENT :** | | | | | |
| 1985 | not measured | | | | |
| 1986 | 0.8 | = | 0.7 | 0.5251 | 0.7 |
| 1987 | 0.6 | < | 1.5 | 0.0031 | 0.5 |

Note: All measurements are in cm. Upland and Lowland means are tested for equality by a T-test. The probability of a greater value of t, under the null hypothesis that the means are equal, is given for each pair. Treatment means that differ from the control means, at the 95 % level, are underlined.

Had the present study been established as a herbicide efficacy study, many of the above parameters affecting efficacy could have been addressed properly. In the absence of such a study, it is both speculative and unproductive to guess why better herbicide efficacy was not attained. In the context of the present environmental impact study, glyphosate is seen to have performed the job it was intended to do and to have provided better than expected silvicultural performance.

Silviculturally, no long-term crop injury was sustained as a consequence of glyphosate use. Hemlock and cedar leaders from 1984 growth were burned off in 1985, following the late 1984 herbicide application. However, complete recovery of hemlock and cedar was achieved by 1986, and 1985 lateral growth often surpassed that attained in 1984 prior to treatment.

Diameter and diameter-increment growth of spruce and hemlock were improved following glyphosate treatment. Increases in diameter growth were clearly traceable to the glyphosate treatment, since no significant differences in this type of growth existed between treated and control trees prior to herbicide treatment. Although spruce height and height-increment for treated trees continued to differ significantly from that for control trees following treatment, it is doubtful that this difference can be safely ascribed to the glyphosate treatment since growth prior to herbicide treatment was also significantly different for the two sets of trees. A significant difference in cedar floodplain root-collar diameter increment for 1987 as contrasted with lower slope trees, may stand as further evidence that glyphosate treatment has enhanced crop growth for all three crop species examined.

Operational and environmental constraints of the present study precluded the selection of additional control trees. Spraying was conducted in response to predetermined limitations as to what had to be or what could not be treated. Hence, controls were not selected by choice, but by the process of elimination of areas dedicated for environmental purposes. In the present study, the strength of the crop growth data is statistically weakened by the small number of controls, and the fact that statistically significant growth differences existed between control and treated trees prior to herbicide treatment. Had more areas within the watershed been available for control purposes, it may have been possible to eliminate pre-spray differences, for the two groups of trees, by increasing sampling size, while simultaneously improving the statistical reliability of our data. In the absence of pre-spray differences, it would have been possible to state definitively, that post-spray height or height-incremental growth increases were due to glyphosate treatment, and not the result of other causes.

In light of the statistical limitations of this study, it is probable that the glyphosate treatment may have resulted in silvicultural growth increases greater than can presently be ascribed. This is especially gratifying in light of the advanced weed competition, and the problems associated with optimally controlling this competition, as previously described. It is indeed possible to conclude by saying that had optimal weed control been achieved, and had statistical and experimental design constraints associated with measuring this growth been alleviated, then it is likely that a substantially greater growth response from glyphosate treatment, would have been recorded.

## ACKNOWLEDGEMENTS

We wish to thank Mr. Ron Rowe (Rotor Vegetation Control, Calgary, Alberta) Mr. Tim MacKay (formerly FPMI) and Messrs. Dave Gubbels and Don Chollca (Alpine Helicopters, Calgary, Alberta) for their assistance in aerially applying glyphosate at the Carnation Creek Watershed. In addition, we thank Mr. Jack Dryburgh (MacMillan & Bloedel Ltd.) for his assistance in marking areas of the watershed to be sprayed. We are grateful to the British Columbia Ministry of Forests for providing funding for this research. Finally, we reserve special thanks for Mr. Henry Benskin (B.C. Forest Service) for his untiring devotion to the success of this project.

## LITERATURE CITED

Dryburgh, J.G. 1982. Carnation Creek logging and silvicultural treatment program. pp 36-44. In G.F. Hartman (ed.). Proceedings of the Carnation Creek Workshop, a 10 Year Review. Pacific Biological Station, Nanaimo, British Columbia. 404 p.

King, R.K. and E.T. Oswald. 1982. Revegetation of Carnation Creek Watershed. pp 110-128. In G.F. Hartman (ed.). Proceedings of the Carnation Creek Workshop, a 10 Year Review. Pacific Biological Station, Nanaimo, British Columbia. 404 p.

Reynolds, P.E., J.C. Scrivener, B. Holtby and P.D. Kingsbury. 1989. Overview of Carnation Creek Herbicide Project: historical perspective, experimental protocols and spray operations. This proceedings.

# COMPARISON OF THE EFFECTS OF CHEMICAL (GLYPHOSATE) AND MANUAL CONIFER RELEASE ON CONIFER SEEDLINGS PHYSIOLOGY AND GROWTH ON VEDDER MOUNTAIN, BRITISH COLUMBIA

J. Karakatsoulis, J.P. Kimmins, and R.E. Bigley

Faculty of Forestry
University of British Columbia
Vancouver, British Columbia

## ABSTRACT

Photosynthesis, stomatal conductance, plant moisture stress (PMS), and the associated soil and air temperature and light intensity were investigated during one growing season (1985) on five-year-old Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] seedlings prior to and following release from brush competition by means of manual weeding and herbicide treatment (glyphosate). The release treatments were applied to replicated plots in late May, mid-July and mid-August in 1985. Seedling growth response (root collar diameter and height growth) was measured at the end of the 1985, 1986, and 1987 growing seasons.

Plots treated in May showed an increase in soil temperature at one, three and ten weeks post-treatment. Due to variation in $CO_2$ uptake, PMS and stomatal conductance rates between seedlings prior to treatment application it was difficult to infer treatment effects on seedling physiology.

Seedlings released manually in July showed a significant increase in soil temperature over the July control and July herbicide released plots at one, three and six weeks post-treatment. A slight increase in PMS was evident on the July control seedlings at three weeks post-treatment, but no significant difference was found at six weeks post-treatment.

There was little difference in root collar diameter or height growth between treatments at one, two, and three years post-treatment. A low degree of initial overtopping of seedling leaders by herbaceous and woody vegetation may explain why seedling height, diameter and physiological responses were not significantly improved by any of the treatments in spite of the visual appearance of the plantation, which led to an operational application of herbicide (glyphosate) in the fall of 1985. Poor correlations were found between seedling growth and a competition index. The data suggest that competition from shrubs and herbs was not having a significant net negative impact on the conifer seedlings over the period of the study. Possible reasons for this result are discussed.

## INTRODUCTION

Many of the ecophysiological and ecological effects of releasing conifer plantations from brush competition are still poorly understood and quantified. One of these effects is the sudden change in microenvironmental conditions experienced by the released seedlings. Inadequate recognition of the physiological requirements for acclimation of conifer seedlings to conditions created by release from light competition has sometimes resulted in unacceptable crop seedling mortality or release response (Bigley and Kimmins pers. comm.; Newton et al. 1982).

Bigley and Kimmins (pers. comm.) suggested that heavily shaded conifer seedlings may be benefited more by herbicide release than by manual release. Slow defoliation of overtopping competing vegetation by a herbicide gives the shade leaves of suppressed conifer seedlings a longer period of acclimation to the increasing light intensity than manual brush removal. However, the difference between the herbicide and manual treatments may vary according to the season of treatment application.

In this present study we examined the effect of two weed control treatments (manual removal and herbicide use) on microclimate changes and physiological and growth response of Douglas-fir seedlings at Vedder Mountain, B.C. Similar microclimate and physiological measurements were made on Sitka spruce [*Picea sitchensis* (Bong.) Carr.] seedlings in the Carnation Creek herbicide trial. The specific objectives of the study were:

1. To compare the physiological status (photosynthesis, stomatal conductance, and PMS) and growth in height and root collar diameter of Douglas-fir seedlings subjected to manual and herbicide release treatments at three different times in the growing season at Vedder Mountain.

2. To compare the time course of microclimate changes experienced by the seedlings as a result of the different release treatments.

3. To test the hypothesis (Bigley and Kimmins pers. comm.) that the physiological shock and initial delay in tree growth response of seedlings following release from brush competition is least when release is accomplished with herbicide treatments applied early in the growing season and greatest when seedlings are released manually late in the growing season.

4. To determine the relationship between a competition index (Wagner 1982) and conifer seedling growth.

The following measurements were made prior to and after each treatment:

1. Seedling stomatal conductance, $CO_2$ uptake and plant moisture stress (xylem water pressure potential).

2. Soil temperature (15 cm depth) at base of seedling.

3. Air temperature at the second whorl of each seedling.

4. Seedling height and root collar diameter.

The first three of these measurements were conducted during the first growing season of the study (1985). Seedling height and root collar diameter were measured at the end of 1985, 1986 and 1987 growing seasons.

## STUDY AREA

The main part of the study was conducted on the southeastern slope of Vedder Mountain, Chilliwack, British Columbia (approximately 100 km east of Vancouver) (Fig. 1). The study site was located on two gently sloping (<5%) benches at an elevation of approximately 200 meters. The surrounding area has a slope of 40-50%.

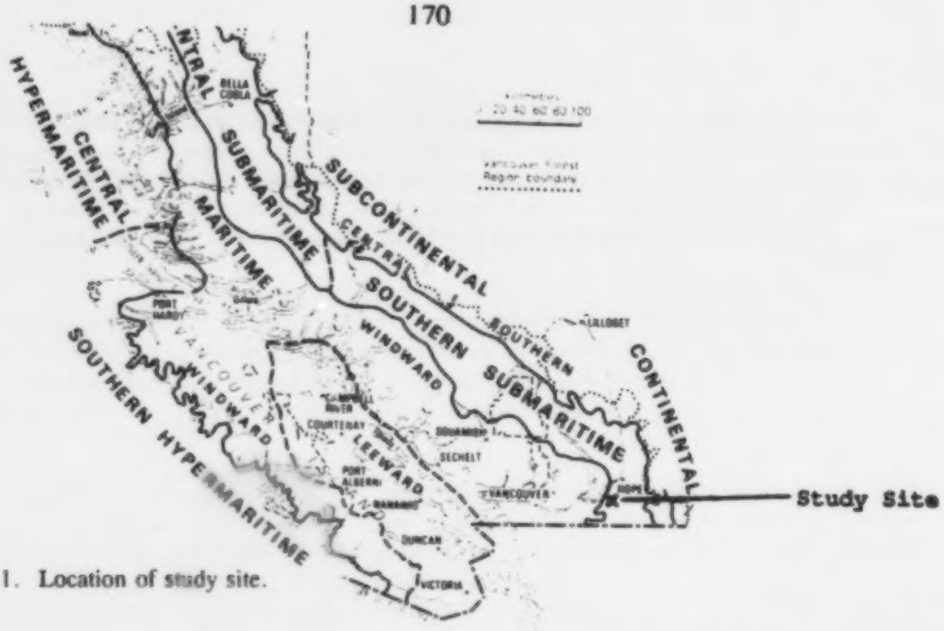

Kilometres
0 20 40 60 80 100
Vancouver Forest Region boundary
CENTRAL HYPERMARITIME
CENTRAL MARITIME
CENTRAL SUBMARITIME
SUBCONTINENTAL
CENTRAL SOUTHERN
SOUTHERN SUBMARITIME
SOUTHERN CONTINENTAL
SOUTHERN HYPERMARITIME
WINDWARD
LEEWARD
VANCOUVER WINDWARD
BELLA COOLA
PORT HARDY
CAMPBELL RIVER
COURTENAY
PORT ALBERNI
NANAIMO
DUNCAN
VICTORIA
SQUAMISH
SECHELT
VANCOUVER
HOPE
LILLOOET
Study Site

Figure. 1. Location of study site.

The soils of the area (as classified by K. Klinka and R. Green, B.C. Ministry of Forests) have a parent material consisting of a surface layer of loess with a silt loam texture consisting of a surface underlain by glacial till with a similar texture. The eolian material is intermixed with the till to some extent due to down-slope movement. Compacted basal till with a loam to clay-loam texture occurs below approximately 80 cm. The coarse fragment lithology is mixed, including sedimentary, metamorphic and medium to dark colored granitic rocks with a medium base status. The humus form is moder to mullmoder with a well developed Ah horizon. Temporary downslope seepage occurs above the basal till. The area receives a mean annual precipitation of 1215 mm. Ecologically, the site falls within the wet subzone of the coastal Douglas-fir biogeoclimatic zone (Krajina 1965).

The study area was originally logged in 1934-38 and it regenerated to a predominantly deciduous stand. This was logged and burned in 1982 and planted with two-year-old Douglas-fir seedlings in 1983. By 1985, the site was judged to be experiencing a brush problem from *Rubus parviflorus*, *Epilobium angustifolium*, *Pteridium aquilinium*, and to a lesser degree from *Sambucus racemosa*, *Prunus emarginata*, *Acer circinatum*, *A. glabrum*, *A. macrophylum* and *Betula* spp.

## METHODS

### Layout of Sampling Plots

The experiment used a completely randomized design with two replicates. Eighteen 20 x 20 m plots (10 x 10 m study plots with a 5-m buffer strip around each plot) were established in the spring of 1985. Each plot was randomly assigned to one of three treatments (manual release, herbicide spray and control) and to one of three release times (late May, mid-July and mid-August). Each treatment/time plot was replicated twice (3 treatments x 3 release times x 2 replicates = 18 plots).

All Douglas-fir seedlings within each plot were tagged at the beginning of the 1985 growing season and initial stem diameter and seedling height were measured on each seedling. The number of seedlings per plot ranged from 8 to 18.

### Treatments

The following treatments were applied at each of the three release periods:

1. *No treatment* (control).

2. *Manual release* - all non-crop vegetation more than 15 cm above the ground was cut and left on the plot.

3. *Herbicide* - glyphosate [N-(phosphonomethyl) glycine] was applied at 2.0 kg/ha a.e. in an aqueous solution by means of a pressurized back-pack sprayer. All Douglas-fir seedlings were covered with large paper bags during herbicide application to prevent damage to the current foliage.

### Sampling Methods

In each plot two seedlings were established as sample seedlings for physiological measurements and at least five seedlings were established for microclimate measurements. These seedlings became permanent sampling points for the duration of the 1985 growing season. Sampling was conducted one week prior to treatment application and at one, three and 10 weeks post-treatment for the May release. The July release sampling was conducted one week pre-treatment and at one, three and six weeks post-treatment. Sampling on the August release plots was conducted at one week pre-treatment and at one week post-treatment. Wet fall weather prevented continued sampling.

At each sampling time, $CO_2$ uptake rates (i.e., photosynthesis), stomatal conductance, plant moisture stress, soil temperature at base of seedling, air temperature at the second whorl of each sample seedling, and the intensity of light reaching the top of the seedling were measured.

### Photosynthetic Determination

The photosynthesis rate of the Douglas-fir seedlings was determined using the $^{14}CO_2$ - labelled air technique as described by Shimshi (1969) and Price *et al*. (1986). This technique involved the placement of excised needles (excised just prior to measurement) into a portable gassing chamber where the needles are exposed to $^{14}CO_2$-labelled air for a period of 20 seconds. Gas flow rate was maintained at approximately 2.0 mL/s by means of a regulator. After exposure to the gas, the needles were removed and placed into 20 mL glass scintillation vials [Kimble (Owens-Illinois), Toledo, Ohio] containing 2 mL of tissue solubilizer [Nuclear-Chicago Solubilizer (NCS) Amersham Corp., Arlington Heights, Illinois]. The needles were taken back to the laboratory where their $^{14}C$ content was measured by liquid scintillation.

The rate of $CO_2$ uptake for each leaf sample fed with $^{14}CO_2$ was calculated by:

$$CO_2 \text{ uptake } (\text{mg } CO_2 \text{ dm}^{-2} \text{ h}^{-1}) = \frac{240 \, [(DPM - B) \times CCO_2 \times 1.18]}{SAD \times LA}$$

where:

240 = constant to convert the 20 sec pulse to an hourly basis

DPM = dpm from liquid scintillation spectrometer as calculated by the instrument = cpm/ce

cpm = the observed sample counts per minute (corrected for background)

ce = the counting efficiency (expressed as a proportion)

B = background dpm

$CCO_2$ = mg $CO_2$/L $CO_2$ for the specific concentration of $CO_2$ used at a specific temperature

1.18 = the discrimination factor to account for kinetic and biochemical discrimination against $^{14}CO_2$

SAD = the specific activity of the gas expressed as dpm/L $CO_2$

LA = the area of the excised leaf ($dm^2$)

Photosynthetic sampling was limited to between 10:30 AM and 12:00 noon to reduce diurnal variability. Five sets of one-year-old needles were sampled from the second whorl of each sample seedling per sample time. Therefore, each treatment/time consisted of 5 sets of needles x 2 seedlings/plot x 2 replicates = n = 20 samples per treatment/time.

### Stomatal Conductance

Stomatal conductance of Douglas-fir seedlings was determined using a LI-COR LI-700 transient automatic diffusion porometer (LI-COR, Inc., Lincoln, Nebraska). Sample needles were removed from a Douglas-fir twig and immediately placed over the instrument's cuvette where the porometer measured the transient time (in seconds) taken for a specific change in humidity. The stomatal conductance was determined from a calibration curve (calibrated at the beginning of each sampling day), which related transient time to six known resistances. Measurements were made on one-year-old foliage obtained from the second whorl of each sampling seedling (same seedling as used for $CO_2$ uptake determination). Measurements were replicated at least three times per sample seedling using different needles each time. All measurements were made on dry leaves between 10:30 AM and 12:00 noon.

### Light Intensity

Instantaneous light (photosynthetically active radiation) readings ($W/m^2$) were made using a LI-COR Quantum Photometer (LI-COR Inc., Lincoln, Nebraska). Light readings were made at the same point as stomatal conductance and $CO_2$ determination (second whorl of the seedling). A further set of light readings was made 10 cm from the base of each seedling per treatment. For the May release treatments, light measurements were taken prior to the treatments and at 3, 6 and 10 weeks post-treatment, and at one year post-treatment. Measurements for the July treatments were made prior to the treatments and at 3 and 6 weeks post-treatment and one year post-treatment.

### Plant Moisture Stress

Plant moisture stress (xylem water pressure potential) was measured using a portable pressure chamber. Measurements were made on clipped twigs containing current and one-year-old foliage taken from 6-8 seedlings (located in the buffer area) per plot. Sampling was conducted between 1:00 PM and 2:30 PM.

### Soil and Air Temperature

Soil temperature was measured at a depth of 15 cm at the base of each sampling seedling (six seedlings per plot were designated for microclimate measurements) using a dial thermometer. Air temperature was measured at the second whorl position of the same seedling using an electronic psychrometer (Cole-Parmer Instrument Co., Chicago, Illinois). Both soil and air temperatures were measured between 1:00 PM and 2:30 PM.

### Seedling Growth

Seedling stem diameter (at the root collar) and height were measured at the beginning of the 1985 season and at the end of the 1985, 1986 and 1987 growing seasons.

### Competition Index

In the spring of 1985, all Douglas-fir seedlings and their immediately surrounding vegetation within the 18 experimental plots were measured to evaluate a competition index (Wagner 1982). The method involves using the stem of a seedling as a plot centre and collecting the following data from within a 2-m radius plot around the seedling:

1. Height (m) of the seedling
2. Percent cover of each non-crop species
3. Average height of each non-crop species
4. Closest distance of each non-crop species from the seedling
5. Furthest distance of each non-crop species from the seedling. The maximum distance is the radius of plot (2 m)

The data were used to determine the competition index (CI) (Wagner 1982) of each non-crop species:

$$CI = HC/100\,(1/r^1 - 1/r^2)$$

where:

H = the average height of a non-crop species within the 2 m radius plot

C = the percent cover of a non-crop species within the plot

$r^1$ = the distance from the seedling centre to the nearest edge of a non-crop species

$r^2$ = the distance from the seedling centre to the furthest point of the 2 m radius plot where a non-crop species is found*

---

* The notations used here are the same as those used by Wagner (1982).

The total competitive influence (TCI) of non-crop species on a seedling is calculated by:

$$TCI = CI1 + CI2 + CI3 + \ldots + CIn$$

where n = the number of non-crop species in the 2 m radius plot.

### Data Analysis

Due to the different sampling periodicity for the different release dates, statistical comparisons could only be done between treatments within release date.

Treatment effects (based on physiological and microclimate measurements) were compared using an analysis of variance for an unbalanced design. Duncan's multiple range test was used (5% probability level) when significant ($p = 0.05$) treatment differences were determined.

Covariance analysis was used to compare treatment effects on Douglas-fir seedling stem diameter and height. Pre-treatment stem diameter and height were used as co-variates to adjust initial seedling stem diameter and height. Where appropriate, Duncan's multiple range test (on adjusted means) was used to compare treatment means.

Linear regression analysis was used to determine the regression model for the competition index and seedling stem diameter and height.

## RESULTS

### Microclimate Changes and Seedling Physiological Response

May treatment

An increase in soil temperature on the May manual release plots was evident at three weeks post-treatment (Fig. 2). At three weeks post-treatment, soil temperature on the manually weeded plots had increased to 18.2°C as compared to 14.4 and 15.8°C for the May control and herbicide plots, respectively. However, by ten weeks post-treatment (mid-August) the highest soil temperature was found on the herbicide released plots. By that time, considerable herbicide-induced defoliation had occurred, whereas the May manual release plots had re-developed a complete coverage of herb and shrub sprouts. Air temperature around the Douglas-fir seedlings showed little correlation to the treatments (Fig. 3).

Because seedling stomatal conductance, photosynthetic activity and PMS varied prior to the May treatments, it is difficult to draw firm conclusions about post-treatment differences in these parameters (Figs. 4, 5 and 6). The data suggest that seedling physiology was unaffected by any of the treatments.

As an index of vegetation cover, measurements of percent light reaching the ground surface were taken for each treatment over the 1985 growing season and at one time (August) during the 1986 season (Fig. 7). At ten weeks post-treatment (mid-August) the non-crop vegetation on the manually released plots had regrown to a level where only 35% of the incoming light was reaching the ground surface. By August 1986, incoming light levels reaching the ground surface were reduced to less than 20%. In contrast, the herbicide-released plots showed a steady increase in

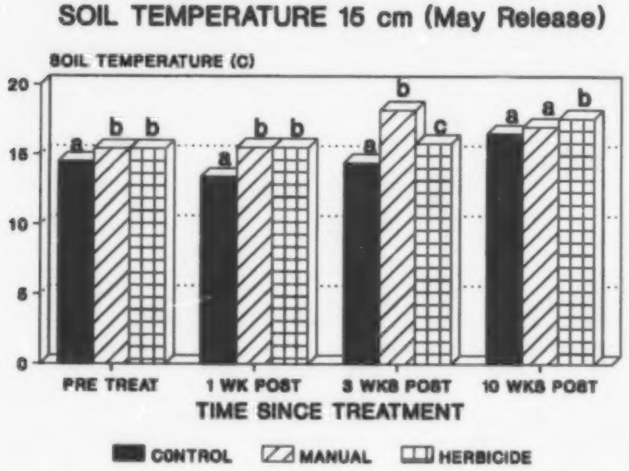


Figure 2. Soil temperature (15 cm depth) changes during the 1985 growing season on the May control, manual and herbicide treatment plots. Means within a treatment time with the same letter are not significantly different at $p = 0.05$.

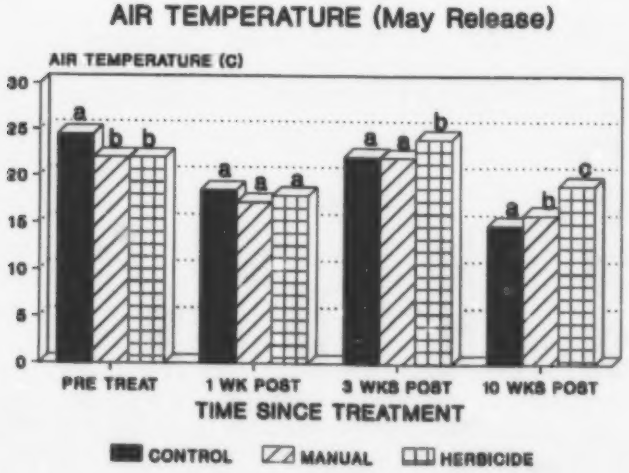


Figure 3. Seedling air temperature changes during the 1985 growing season on the May control, manual and herbicide treatment plots. Means within a treatment time with the same letter are not significantly different at $p = 0.05$.

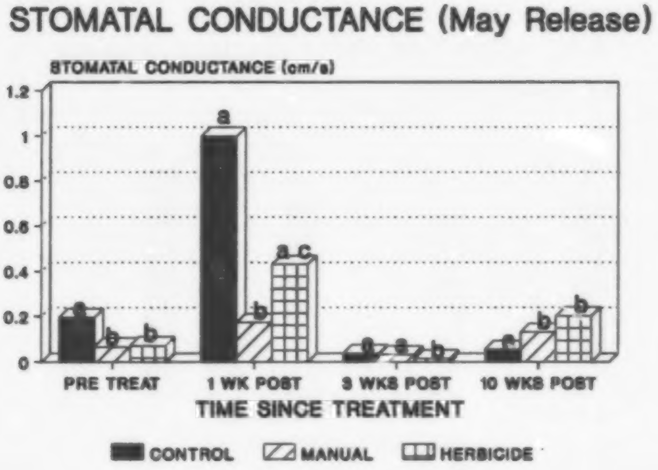


Figure 4. Stomatal conductance of May-released Douglas-fir seedlings at four periods during the 1985 growing season. Point measurements were made between 10:30 AM and 12:00 noon. Means within a treatment time with the same letter are not significantly different at p = 0.05.

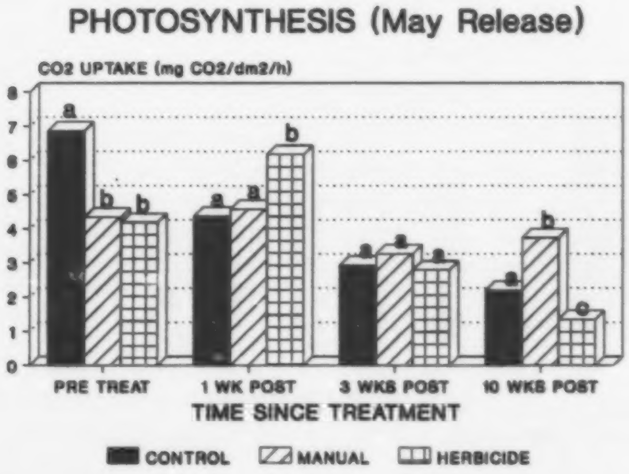


Figure 5. $CO_2$ uptake of May-released Douglas-fir seedlings at four periods during the 1985 growing season. Point measurements were made between 10:30 AM and 12:00 noon. Means within a treatment time with the same letter are not significantly different at p = 0.05.

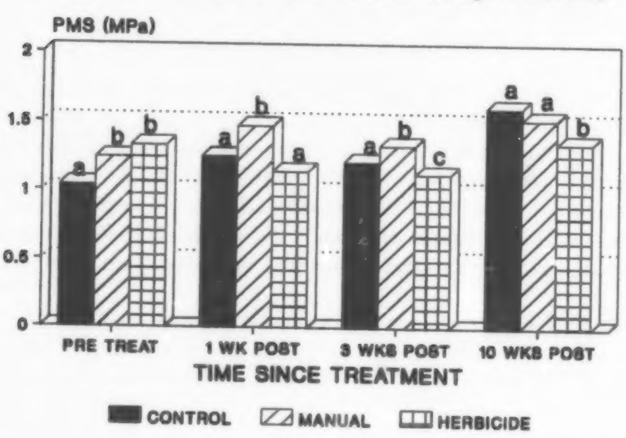


Figure 6. Plant moisture stress (MPa) of the May-released Douglas-fir seedlings during the 1985 growing season. Point measurements were made between 1:00 PM and 2:30 PM. Means within a treatment time with the same letter are not significantly different at p = 0.05.

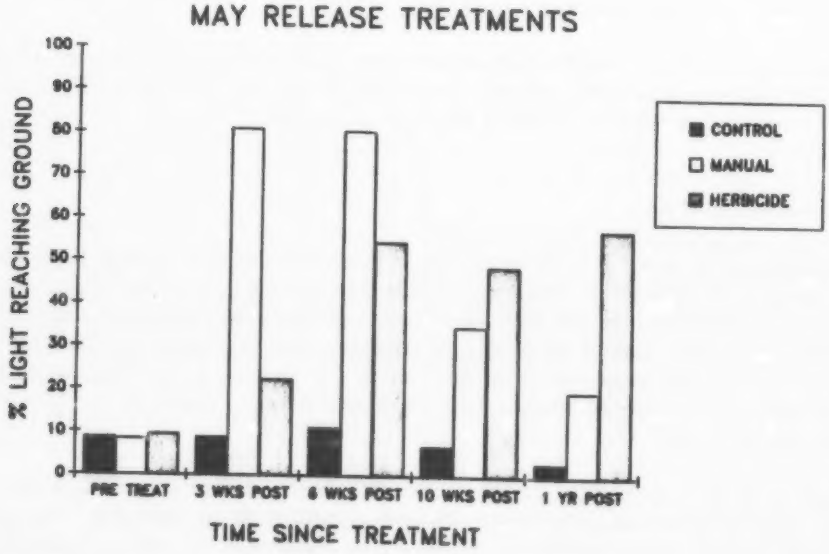


Figure 7. Percent light (PAR) reaching the ground surface on four separate dates during the 1985 growing season and on one day (mid-August) during the 1986 season. Percent light was used as an index of vegetation cover.

light penetration during the 1985 growing season. By the following year, the amount of incoming light reaching the ground surface had reached 58%.

July treatment

Non-crop vegetation that was cut manually in mid-July did not regrow as vigorously as did the vegetation on the May manual release plots. The hot dry weather and the low precipitation during July and August probably limited vegetation regrowth. As a result, soil temperatures on the July manual release plots remained high for the remainder of the 1985 growing season (Fig. 8). Figure 9 shows the percent light reaching the ground as an index of vegetation cover. At six weeks post-treatment the manually released plots were still receiving 85% of available light. PMS, while not varying significantly between treatments, increased from early July to mid-August.

An increase in air temperature around the manually released seedlings was evident one week following vegetation removal. However, by the end of the growing season (1985) there were no seedling air temperature differences between the control, manual and herbicide released seedlings (Fig. 10).

At six weeks following treatment, seedlings on the July herbicide released plots showed higher stomatal conductance rates than the control and manually released seedlings (Fig. 11). Their higher rates may have been due, in part, to a treatment-related decrease in below ground competition. Soil moisture deficits during the growing season may play a greater role in directing vegetation growth than shading effects alone.

Due to pre-treatment differences in photosynthesis between treatment seedlings it is difficult to deduce photosynthetic rates as a function of treatment effect (Fig. 11).

Physiological and microclimate measurements for the August release plots are not shown due to insufficient numbers of sampling periods. Physiological and microclimate sampling was only conducted at one week pre-treatment and at one week post-treatment.

## Seedling Growth Response

Seedling growth response to the three release treatments and three release times was monitored over three growing seasons. Because initial seedling stem diameter and height varied at the beginning of the experiment, growth data was analyzed using an analysis of covariance. Seedling stem diameter at the beginning of the 1985 growing season was used as the covariate for stem diameter, while the 1984 height measurement was used as the covariate for seedling height growth. Figures 14 and 15 show adjusted seedling height and stem diameter means for the May, July and August released seedlings.

Seedling height and diameter growth after three growing seasons showed little difference between the May, July and August released seedlings regardless of the treatment. The modest degree of over-topping of the seedlings by the shrubs and herbs and the relatively good initial vigor of the Douglas-fir seedlings may account for the low seedling response to the release treatments. Harrington and Wagner (1986) found similar results in a three-year study comparing Douglas-fir seedling growth response to five release treatments on six sites in western Washington and Oregon. Glyphosate and manual cutting were two of the treatments used in their study.

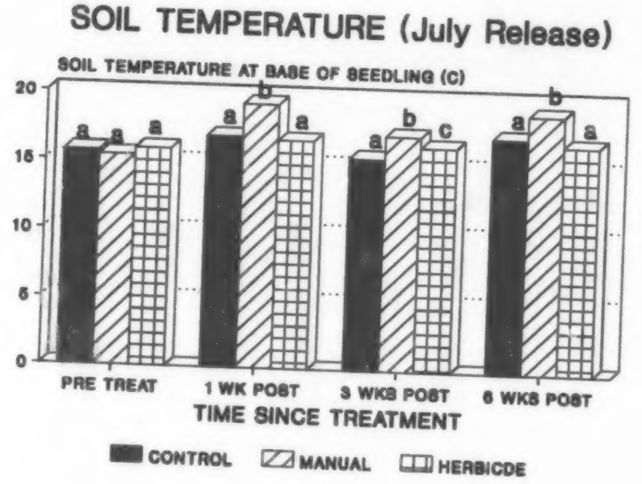


Figure 8. Soil temperature (15 cm depth) changes during the 1985 growing season on the July control, manual and herbicide treatment plots. Means within a treatment time with the same letter are not significantly different at $p = 0.05$.

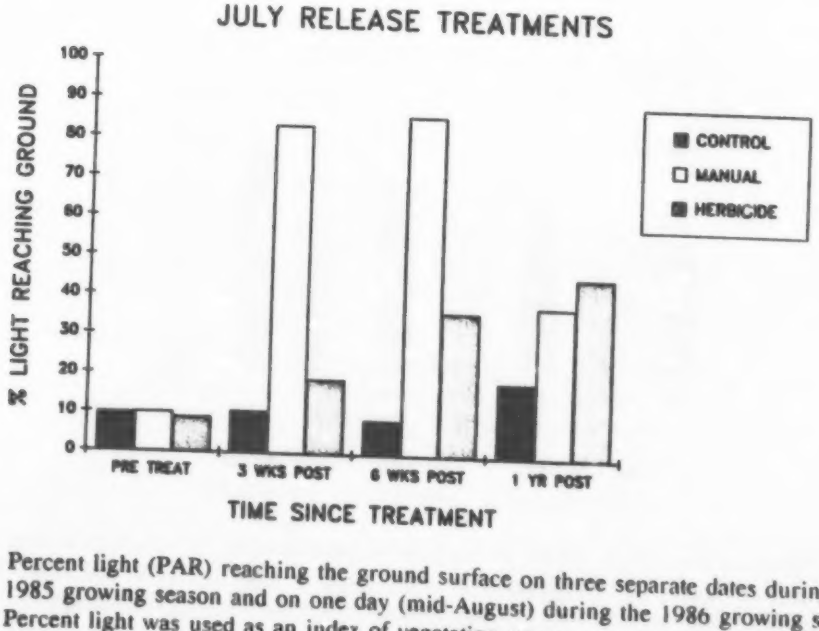


Figure 9. Percent light (PAR) reaching the ground surface on three separate dates during the 1985 growing season and on one day (mid-August) during the 1986 growing season. Percent light was used as an index of vegetation cover.

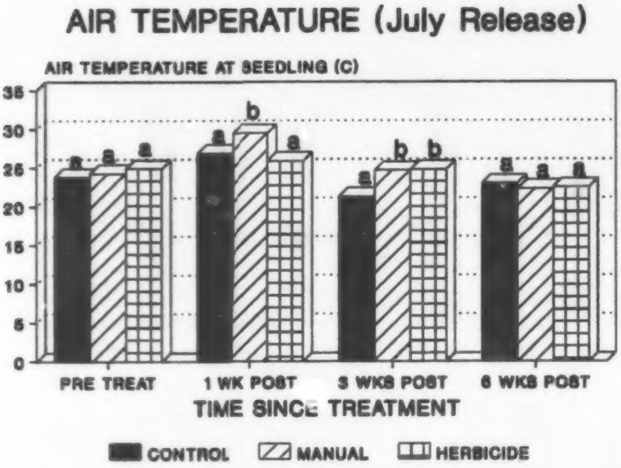


Figure 10. Air temperature (July release).

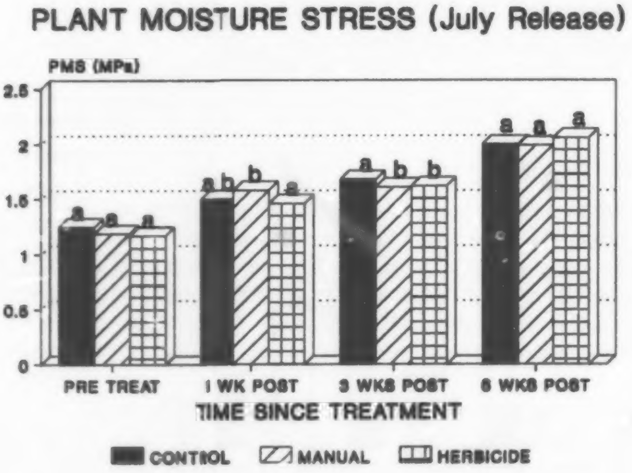


Figure 11. Plant moisture stress (MPa) of the July-released Douglas-fir seedlings during the 1985 growing season. Point measurements were made between 1:00 PM and 2:30 PM. Means within a treatment time with the same letter are not significantly different at $p = 0.05$.

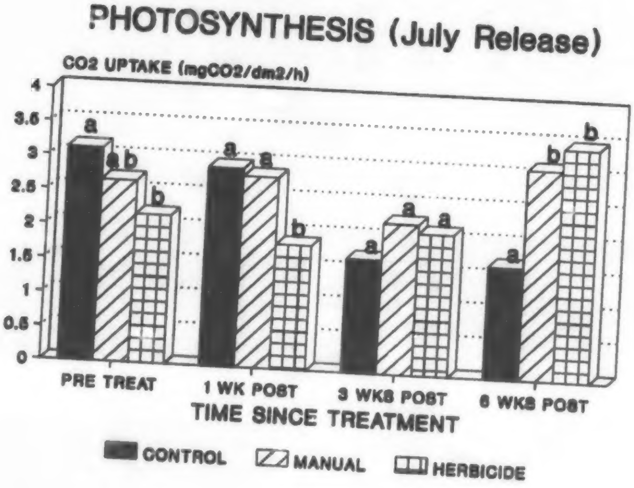


Figure 12. $CO_2$ uptake rates of the July-released Douglas-fir seedlings at four periods during the 1985 growing season. Point measurements were made between 10:30 AM and 12:00 noon. Means within a treatment time with the same letter are not significantly different at p = 0.05.

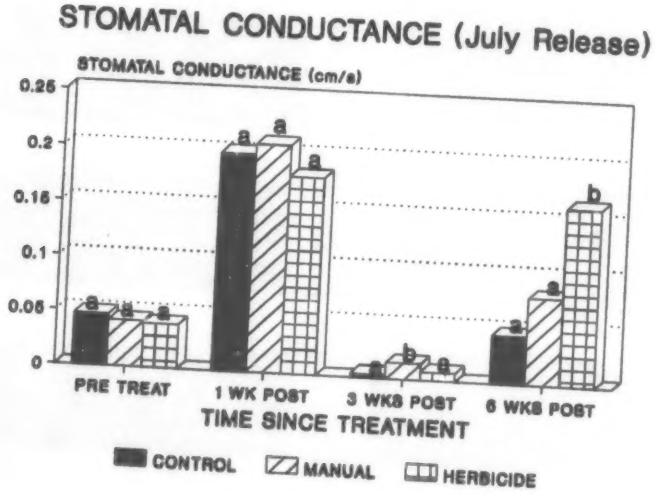


Figure 13. Stomatal conductance of July-released Douglas-fir seedlings at four periods during the 1985 growing season. Point measurements were made between 10:30 AM and 12:00 noon. Means within a treatment time with the same letter are not significantly different at p = 0.05.

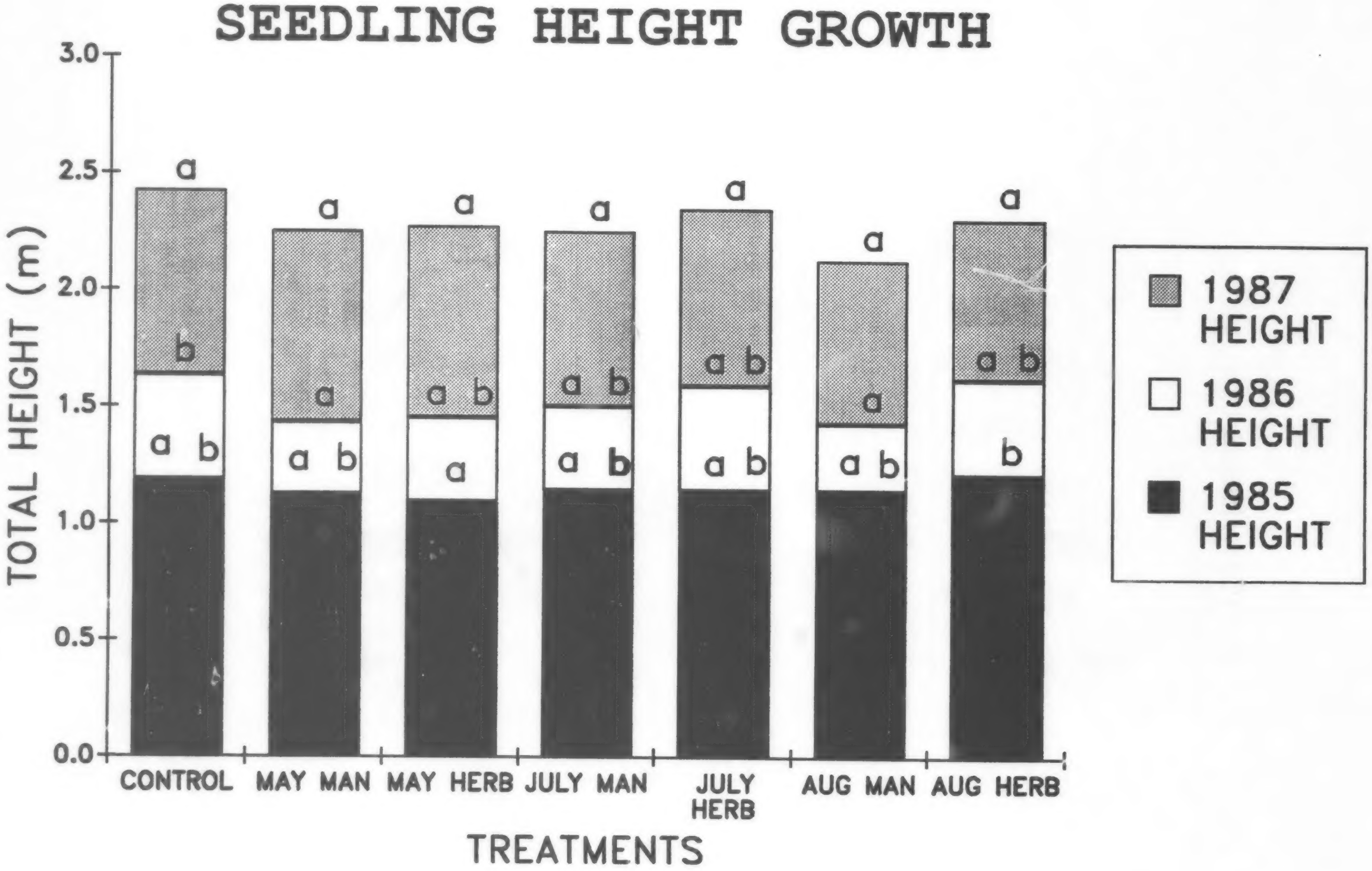


Figure 14. Seedling height growth.

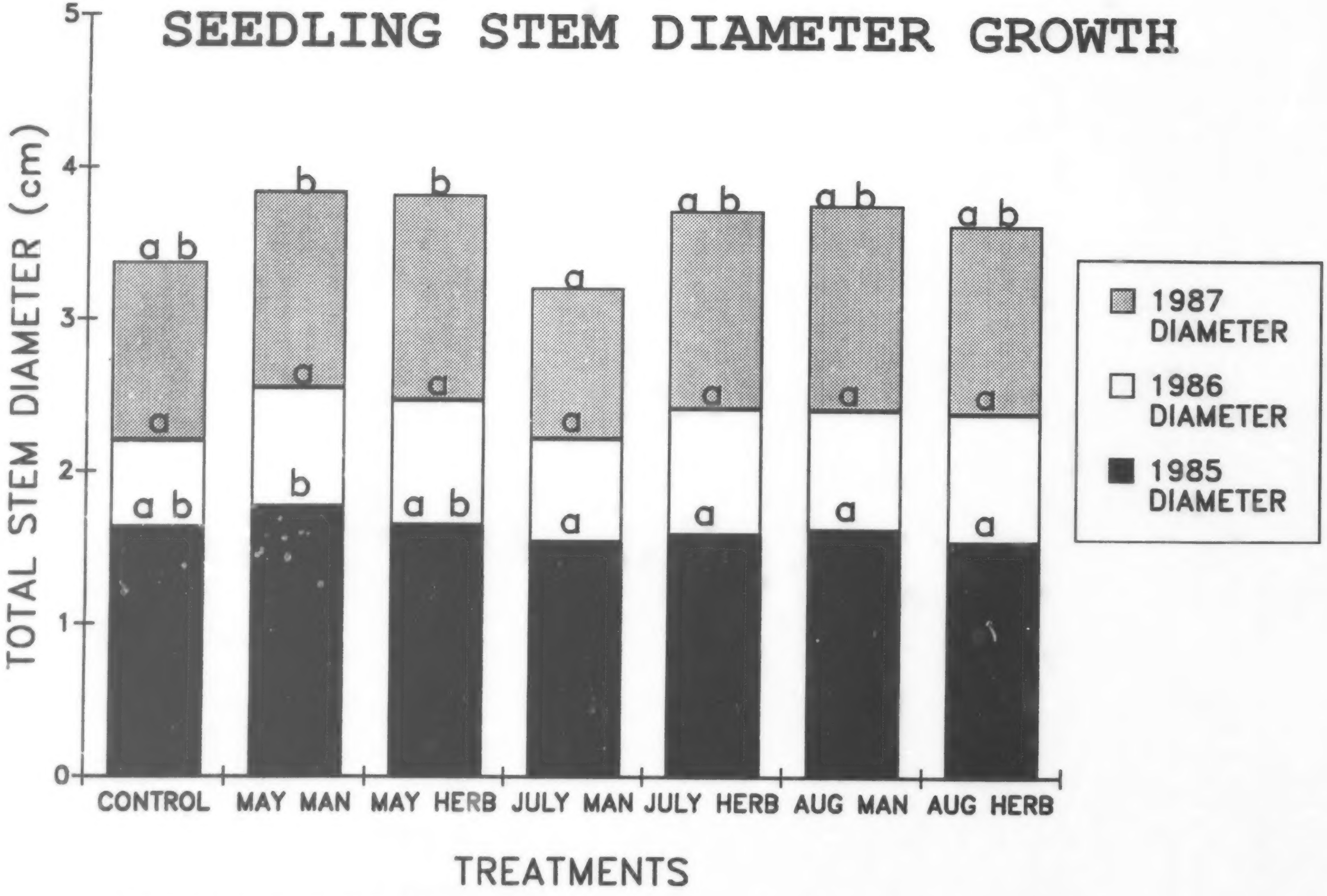


Figure 15. Comparison of adjusted treatment means for Douglas-fir stem diameter (root collar) at the end of the 1985, 1986 and 1987 growing seasons. Means within a treatment time with the same letter are not significantly different at $p = 0.05$.

**Competition Index**

One hundred and ninety-six Douglas-fir seedlings were measured (total height and stem diameter at the root collar) at the beginning of the 1985 growing season and their total competitive index (TCI) determined. A simple regression analysis of Douglas-fir seedling height on TCI ($r^2 = 0.01$) showed no significant correlation at the 0.05 probability level (Table 1). However, at $p < 0.05$ the regression of Douglas-fir stem diameter on TCI showed a significant correlation even though there was a very low $r^2$ value (0.04) (Table 1).

The low correlation between Douglas-fir seedling growth (stem diameter and height) and the competitive index suggests that either:

1) there was little influence on the Douglas-fir seedling growth by the surrounding vegetation at this early stage of plantation establishment, or,

2) the competitive index used is insensitive to the effects of specific site parameters (soil moisture, nutrients, temperature). The index assumes all vegetation has a negative effect on conifer growth.

Table 1. Linear regression equations predicting Douglas-fir seedling stem diameter and height based on competition index (CI) value

| Variable | Equation | n | $r^2$ | F |
|---|---|---|---|---|
| Diameter | $y = 1.491 - 0.093$ (CI) | 195 | 0.04 | 8.601* |
| Height | $y = 1.085 - 0.035$ (CI) | 195 | 0.01 | 1.734 |

* Significant at $p = 0.05$

## DISCUSSION

Kimmins et al. (1986) found an increase in photosynthetic rates of severely suppressed Douglas-fir saplings following early season manual and herbicide release from a red alder (*Alnus rubra* Bong.) overstory, whereas mid-summer manual release resulted in a depression of photosynthesis. In contrast, few of the Douglas-fir seedlings on the Vedder Mountain site were completely suppressed by the surrounding vegetation and the Douglas-fir were continuing to put on good height growth, whereas the herbs and shrubs did not show any significant increase in height over the three years of the study. The modest height growth of the thimbleberry and bracken fern on the site is attributed to its southerly aspect and associated growing season moisture stress. However the herb and shrub cover were restricting invasion of the site by deciduous hardwood tree species which constitute a more severe competitive threat to the Douglas-fir seedlings. Although there was some deciduous tree growth on the plots, it had not yet reached the stage of exerting significant light competition on the conifer seedlings.

The low growth response of Douglas-fir seedlings over a three-year period to the two release treatments indicate that a better understanding of crop non-crop interactions on different sites are needed before major treatment applications are made. While it is probable that the 1985 broadcast herbicide treatment might have had long-term beneficial effects because of the early control of deciduous hardwoods, the results of our experiment suggest that it may have achieved little in the short term on this particular site. Removal of the deciduous trees by the herbicide may have reduced subsequent competition problems, on the other hand, removal of herbs and shrubs might permit increased invasion by competitive hardwood species. Only long-term studies (20 years) would answer the question as to the overall long-term efficacy of the treatment. Unfortunately, destruction of the vegetation in the study area by wildfire in October 1987 prevented the continuation of this particular experiment.

## CONCLUSIONS

1. Douglas-fir seedlings released by manual and herbicide treatment showed little differences in stem diameter and height growth after 1, 2, and 3 growing seasons regardless of when the seedlings were released.

2. May herbicide-released plots showed a steady increase in soil temperature (15 cm depth) over the growing season due to the slow defoliation of the vegetation and the concomitant increase in solar radiation reaching the ground surface.

3. Herbs and shrubs cut in mid-July regrew slowly resulting in high soil temperatures on the July manually released plots for the remainder of the growing season. Rapid regrowth on the May manually released plots prevented similar soil temperature increases on these plots.

4. Photosynthetic rate, stomatal resistance and plant moisture stress (xylem water pressure potential) of Douglas-fir seedlings did not vary significantly between treatments. Part of the lack of significance related to pre-treatment differences between the seedlings.

5. The low degree of initial overtopping of the Douglas-fir seedlings by herbs and shrubs may explain why seedling growth was not improved by the treatments. Although the site appeared to very brushy, levels of light competition were probably not inhibitory.

## LITERATURE CITED

Bigley, R.E. 1988. Ecological physiology of conifer seedlings and sapling suppression by, and release from, competing vegetation. Ph.D. thesis. Univ. of B.C., Vancouver, B.C. pp 133.

Harrington, T.B. and R.G. Wagner. 1986. Three years of Douglas-fir growth and survival following six competition release treatments in the Oregon and Washington Coast Range. CRAFTS Report. Forest Research Laboratory, Oregon State Univ., Corvallis, Oregon.

Kimmins, J.P., K.A. Scoular, R.E. Bigley, W. Kurz, P.G. Comeau and L. Chatarpaul. 1986. Yield prediction models: the need for a hybrid ecosystem-level approach incorporating canopy function and architecture. pp 26-48 In Proc. Crown and Canopy Structure in Relation to Productivity. T. Fujimori and D. Whitehead (eds.) Forestry and Forest Products Research Institute, Ubarake, Japan.

Krajina, V.J. 1965. Biogeoclimatic zones and classification of British Columbia. Ecol. West. North America 1:1-17.

Newton, M., D.E. White and B.R. Kelpsas. 1982. Growth response of Douglas-fir after herbicide application and hand clearing. In Proc. West. Soc. Weed Sci., March 9-11, 1982, Denver, Colorado.

Price, D.T., T.A. Black and F.M. Kelliher. 1986. Effects of salal understory removal on photosynthetic rate and stomatal conductance of young Douglas-fir trees. Can. J. For. Res. 16:90-97.

Shimisi, D. 1969. A rapid field method for measuring photosynthesis with labelled carbon dioxide. J. Exp. Bot. 20:381-401.

Wagner, R.G. 1982. A system to assess weed severity in young plantations for making management decisions. Forest Management Workshop. Oregon, State Univ., Corvallis, Oregon.

# APPENDIX I

## Carnation Creek

In 1984, a study was undertaken to evaluate the growth response of planted 5-year-old Sitka spruce (*Picea sitchensis*) seedlings and non-crop vegetation growth response to an aerial herbicide application (glyphosate @ 2.0 kg/ha applied by helicopter using a MICROFOIL BOOM) in the Carnation Creek watershed on the west coast of Vancouver Island. At the time of herbicide application the spruce seedlings were overtopped by red alder (*Alnus rubra*) with an associated understory component consisting primarily of salmonberry (*Rubus spectabilis*) and fireweed (*Epilobium angustifolium*).

This study reports on Sitka spruce seedling physiology and microclimate differences between the herbicide treatment and the control (no treatment) at one sampling period during the 1985 growing season (July 31, 1985).

## Methods

The variables measured and the methods used for sampling seedling physiology and micro-environmental parameters are the same as in the Vedder Mountain study (this report). As well as sampling one-year-old foliage for CO uptake and stomatal conductance, current foliage was also sampled. Sampling was conducted on three control and three herbicide plots established by Keith Kane and Roger Whitehead of the Pacific Forestry Centre, Victoria.

Two seedlings per plot were used for physiological measurements for a total of six seedlings per treatment.

## Results and Discussion

No significant difference was found between the control and the herbicide treatment (Table 2) for seedling stomatal conductance (both one-year-old and current foliage), plant moisture stress, soil temperature (15 cm depth) and air temperature. CO uptake of spruce seedlings varied between treatments, being significantly higher for herbicide released seedlings than for the control seedlings for both one-year-old and current foliage (Table 2). Light levels, although relatively low, were twice as high in the herbicide plots (22.8 W/m$^2$) than in the control plots (10.7/ W/m$^2$) and may account for the higher photosynthetic rates for spruce seedlings growing in the herbicide treated plots.

The data suggest that on these humid, moist sites, photosynthesis, as it relates to light intensity, may be the main physiological parameter limiting growth of Sitka spruce.

In comparing the competitive situation at Vedder Mountain and Carnation Creek, we need to know the seasonal course of photosynthesis and of photosynthesis-limiting conditions: light, temperature, moisture and nutrients. This requires knowledge of the seasonal course of competing leaf area development, adverse soil and air temperatures, and moisture. In conclusion, the midsummer studies are probably not very helpful in vegetation management. We need to understand the seasonal course of crop and non-crop physiology, and in the parameters determining physiology and growth. Midsummer competition indices are likely to fail unless winter photosynthesis and growth of conifer seedlings coincides with maximum leaf area of the competing non-crop vegetation.

**Table 2. Summary statistics for Carnation Creek Sitka spruce seedling physiology and treatment microenvironment data**

| | Treatment means (sd) | | |
|---|---|---|---|
| | Control | Herbicide | P |
| Light (Wm$^{-2}$) n = 61 | 10.7 (10.0) | 22.8 (11.1) | 0.001 |
| Air. temp. (°C) n = 15 | 17.5 (0.4) | 17.5 (0.3) | 0.581 |
| Soil temp. (°C) n = 16 | 15.2 (0.9) | 15.3 (1.1) | 0.681 |
| PMS (MPa) n = 17 | 1.01 (0.16) | 1.01 (0.15) | 0.979 |
| Stomatal* conductance (cm.s$^{-1}$)<br>current foliage n = 25 | 0.04 (0.05) | 0.05 (0.06) | 0.152 |
| 1-yr-old foliage n = 24 | 0.07 (0.09) | 0.04 (0.07) | 0.312 |
| CO$^2$ uptake (mg CO$^2$ .dm$^{-2}$.h$^{-1}$)<br>current foliage n = 30 | 4.4 (4.1) | 15.9 (8.4) | 0.001 |
| 1-yr-old foliage n = 30 | 4.5 (4.9) | 17.7 (9.9) | 0.001 |

# CROP TOLERANCE OF THREE WEST COAST CONIFER SPECIES TO GLYPHOSATE

Raj Prasad
Forest Pest Management Institute
Canadian Forestry Service
P.O. Box 490
Sault Ste. Marie, Ontario P6A 5M7

## ABSTRACT

A greenhouse and nursery study was conducted using three species of western conifers, (*Picea sitchensis* [Bong] Carr., *Pseudotsuga menziesii* [Mirb.] Franco and *Thuja plicata* Donn), to evaluate their levels of tolerance to glyphosate sprayed at 2.1 kg a.i. in 380L water/ha. It was found that the degree of tolerance was dependent upon the stage of development ("hardening") of the foliage. Young and tender needles (4-8 weeks after bud-flush) were more sensitive to glyphosate exposure than mature needles, which had developed for 12 weeks or longer after the flush. Whether the conifers were flushed under controlled greenhouse conditions (temp. 20 ± 1°C, relative humidity 70 ± 5%, light 22000 lux, photoperiod 16:8 light:darkness) or outside in the nursery, a minimum of 12 weeks after flush was required for the needles to resist the impact of the maximum recommended dosage of the herbicide. Western red cedar was found to be the least resistant species, showing unacceptable damage even 12 weeks after flush. Because foliar selectivity appears to be related to "hardening" of the needles, it is suggested that spraying operations be synchronized with the completion of this process (about 12 weeks after flush) for maximum crop tolerance. The mechanisms underlying the causes of seasonal tolerance of conifers to herbicide (glyphosate) are also discussed.

## INTRODUCTION

Herbicides are now regarded as one of the most cost-effective and efficient tools for the regeneration of coniferous forest in Canada (Sutton 1978, 1984; Wood and Campbell 1984). Among the forestry herbicides used today, glyphosate [N-(phosphonomethyl) glycine] is beginning to play an increasingly important role in forest management, for site preparation and conifer release operations (Newton 1977; Monsanto 1982; Prasad 1984a; Reynolds et al. 1986). Despite its well-documented success, varying degrees of crop damage have been reported when glyphosate was applied in certain forest nurseries in eastern Canada (Hallet 1985). Reynolds et al. (1986) also reported observing injury to western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) following aerial application of glyphosate at Carnation Creek. Information is lacking on the response of western conifers to treatment with glyphosate at specific periods during the early growing season. This study was undertaken in an attempt to address the problem.

## MATERIALS AND METHODS

### Culture of Plants

After application of the appropriate stratification treatments, certified seed of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, Sitka spruce, *Picea sitchensis* (Bong) Carr., and western red cedar, *Thuja plicata* Donn, were germinated in a nursery bed at the B.C. Provincial Nursery, in Surrey, B.C. When the plants reached the 2+2 years stage, the most vigorous seedlings of each species were lifted from the bed and shipped to the greenhouse in Sault Ste. Marie, Ontario. Plants were received during the winter in a semi-dormant state, having already completed the previous year's growth cycle. All seedlings were replanted into individual polystyrene pots (15 x 15 cm) filled with a bedding mixture of peat moss and soil (1:1 v/v) which had been sterilized to prevent damping off by *Pythium* spp. Dormancy was maintained by storing the plants in a coldroom until required.

In the spring, a portion of the original batch of seedlings from each species was returned to the greenhouse where flushing was induced under controlled conditions [temperature 20±1°C, light 22000 lux, 16:8h diurnal light:dark period and relative humidity 70±15%]. Incandescent and fluorescent bulbs were used to simulate natural daylight. Surface irrigation with a standard nutrient solution and frequent watering yielded seedling growth of excellent vigour and uniformity. The remaining plants were put outdoors in a nursery and allowed to flush under the natural climatic conditions of the Sault Ste. Marie growing season (June-August 1985). Average temperature, relative humidity and light intensity in the nursery during the growing period was ca 16°C, 75% and 45000 lux, respectively.

### Treatment of Plants and Response Measurement

Replicate sets of 10 seedlings of each species were removed from the greenhouse at intervals of 4, 8 and 12 weeks after the commencement of bud-flush and were sprayed with glyphosate (2.1 kg ai/380L/ha). Conifers grown outdoors in the nursery were treated only after the 12-week interval.

Herbicide applications were conducted in a spray chamber with the spray mix applied directly onto the foliage (needles). Spraying parameters were: sprayer speed - 4 km/h; pressure - 205 kPa.; nozzle type - D8-46; volume rate - 380 L/ha. Rhodamine dye (@ 0.1% v/v) was added to the formulation prior to spray and droplet spectra produced by the nozzle were collected on Kromekote cards. Cards were analyzed for droplet size, number and volume using a standardized procedure (Cadogan et al. 1986; Prasad and Cadogan 1987). The spread factor of glyphosate droplets on Kromekote cards was calculated and a linear relationship between stain size and droplet diameter was established (Fig. 1). From this relationship, the actual diameter and volume of glyphosate droplets were calculated.

After spraying, the treated plants were brought to a post-treatment chamber in the greenhouse and maintained under the same conditions at which they were grown. To assess the crop tolerance quantitatively, a standardized format was used to derive an estimate of percentage injury (0-100%) to the needles of each plant (Prasad 1984b). Response was also measured by changes in fresh weight of conifer needles. Evaluations were made 3 weeks after treatment.

### Statistical Treatment

The data were analyzed using Duncan's multiple range test (Duncan 1955). Where necessary, data on percentages were transformed to angular arc sin to minimize variability in the treatments. To determine the relationship between droplet and stain size, linear regression analysis was used to determine the line of best fit.

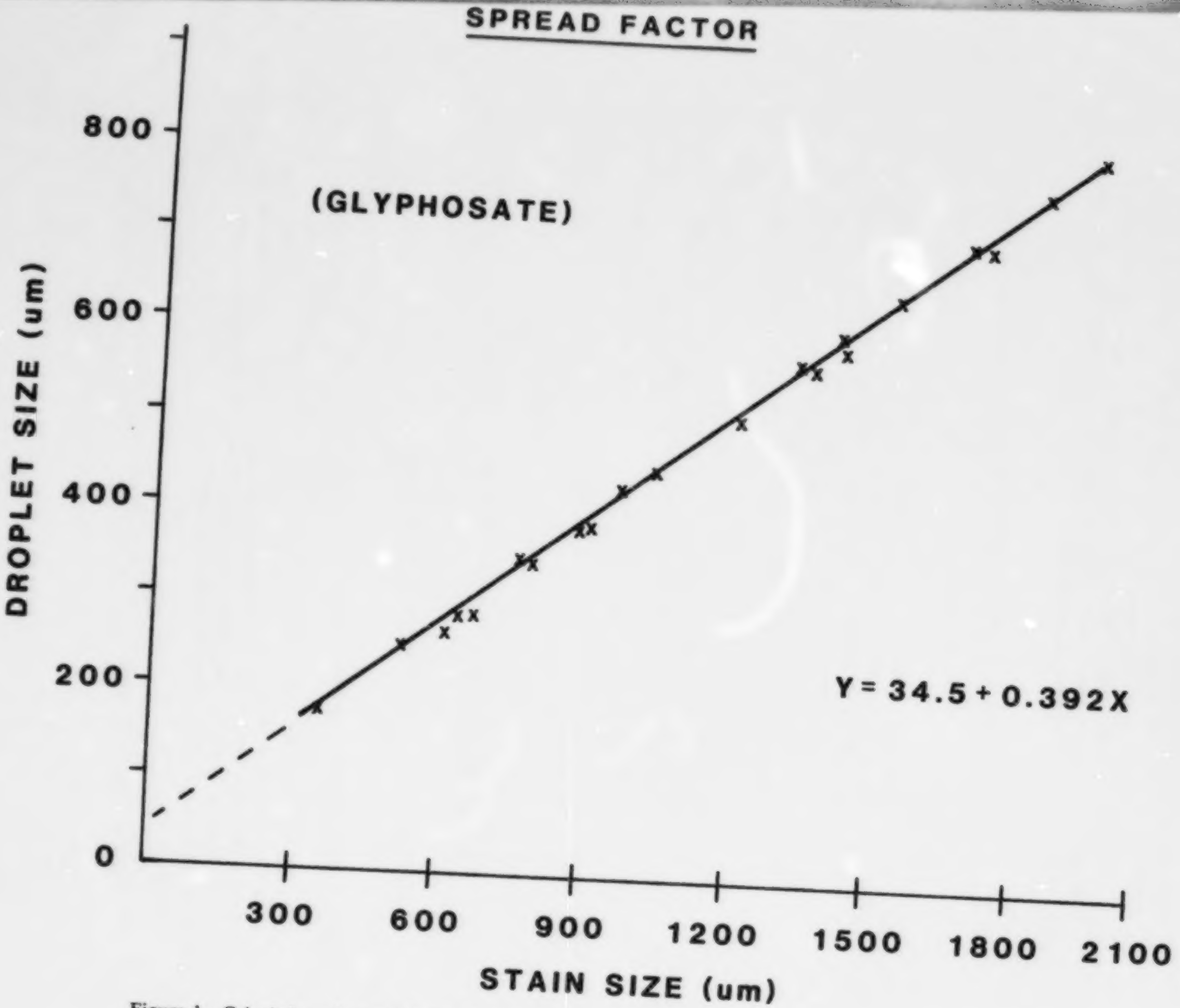


Figure 1. Calculation of spread factor of glyphosate droplets on a Kromekote card.

## RESULTS AND DISCUSSION

### Droplet Characteristics of Glyphosate Sprays

Tables 1 and 2 show that when glyphosate formulation (2.1 kg/380L/ha) was applied to the three conifer species with the D8-46 nozzle, a good distribution of spray was achieved on the target needles. About 43% of the droplets were small (ca 100 μm), 30% were in the 210 μm size-class and 16% in the 330 μm size-class. There were very few droplets of large size (>450 μm). Only three droplets of 800 μm or greater were registered, but because this might have been due to coalescence and fusion, less importance is attached to these classes of droplets.

Table 1. Droplet spectrum of glyphosate spray following delivery from the nozzle (D8-46)[a]

| Stain size (mid-class point) (μm) | Droplet frequency (per $cm^2$) | Droplets in each class (%) | Droplet diameter (μm) | Volume/ droplet (μL) | Total volume per size class (μL) |
|---|---|---|---|---|---|
| 150 | 113 | 43 | 93 | 0.0004 | 0.048 |
| 450 | 78 | 30 | 211 | 0.004 | 0.384 |
| 750 | 41 | 16 | 329 | 0.180 | 0.765 |
| 1050 | 17 | 6 | 446 | 0.046 | 0.790 |
| 1350 | 5 | 2 | 564 | 0.093 | 0.470 |
| 1950[b] | 8 | 3 | 799 | 0.263 | 2.343 |

[a] Glyphosate sprayed 2.1 kg/380 L/ha on Kromekote card; spread factor y = 34.5 + 0.392X.

[b] Individual droplets non-discrete at large diameter.

### Effects of Glyphosate on Crop Tolerance

Results based on the evaluation of crop damage (Table 3) show that needles developing at the 4 and 8 week stages in the greenhouse were less tolerant to glyphosate exposure than those grown for a 12-week period in either the greenhouse or nursery. Those conifers that had been flushed for 12 weeks in the nursery showed the greatest tolerance to the glyphosate applications. These results agree with the findings of Willis et al. (1987).

Table 2. Distribution of (a) glyphosate droplet sizes on Kromekote card and (b) measurement of droplet number and diameters following spray from the nozzle (D8-46)[a]

| | Classes of droplets (µm) | Distribution of number (% of total) |
|---|---|---|
| (a) | <150 | 43 |
| | 150-500 | 52 |
| | >500 | 5 |

(b)

Droplet density (no./$cm^2$) - 260[b]
NMD (µm) - 178
VMD (µm) - 570
D(max) (µm) - 750
D(min) (µm) - 40

[a] Glyphosate (2.1 kg/380L/ha) sprayed with 0.1% Rhodamine dye and measured on Kromekote cards. Spread factor calculated from equation $y = 34.5 + 0.392x$ : where y is the droplet; x is the stain.

[b] Mean of 3 squares/card.

Table 3. Influence of glyphosate (2.1 kg/ha) on phytotoxicity to western conifers at different stages of development in greenhouse and nursery

| | Phytotoxicity (%) | | | |
|---|---|---|---|---|
| | Weeks after flush | | | |
| | (Greenhouse) | | | (Outdoor nursery) |
| Species | 4 | 8 | 12 | 12 |
| Douglas-fir | 35.4[a] | 40.1[a] | 3.8[b] | 0.0[c] |
| Sitka spruce | 26.2[d] | 8.5[e] | 3.1[f] | 1.1[g] |
| Western red cedar | 20.2[l] | 23.4[l] | 12.1[m] | 7.1[n] |

[a-n] Means followed by the same letter are not significantly ($P = 0.05$) different by Duncan's multiple range test.

Of the three species tested, Douglas-fir was the most sensitive to glyphosate after 4 weeks of needle development. Sitka spruce hardened at a faster rate than either of the other two species and by 8 weeks seemed to be reasonably tolerant to glyphosate. Although western cedar exhibited some herbicide damage even when treated 12 weeks after flush, the general trend among the conifer species is towards a gradual decrease in susceptibility to glyphosate over the hardening-off period. The actual degree and duration of this susceptibility appears to be a species-specific characteristic.

Several factors influence the formation, maturation and development of needles in conifers. Martin and Juniper (1975) and Willis et al. (1987) found that deposition of waxes, cuticle and their combinations are greatly affected by the environmental conditions under which conifers grow and develop. This may help explain the greater tolerance to glyphosate exhibited by seedlings allowed to flush out of doors for 12 weeks over those induced to flush for the same period in the greenhouse. They also reported that white spruce needles produce a bloom of waxes earlier in their developmental stages which seems to confer resistance to moisture loss and probably to penetration and translocation of herbicides. Using scanning electron microscopy and chemical methods, previous researchers (Radosevich et al. 1980; King and Radosevich 1985; and Willis et al. 1987), showed that maturation of the conifer needle is tightly coupled with formation of these blooms of waxes and cutin on the needle surface.

Other physiological changes that take place in these conifers may also affect the phytotoxic behavior of glyphosate. Radosevich et al. (1980), for example, attributed the increased tolerance to a lower growth rate and lower transpiration (xylem) potential of the conifers. On the other hand, some investigators (Lund-Hoie 1985; McCormack et al.1981) have suggested that seasonal variations in conifer tolerance to herbicides are due to more advanced dormancy. Their reasoning was based on the observations that conifers are usually more sensitive to herbicide sprays when new shoots are elongating but that this sensitivity rapidly declines when elongation ceases at earlier growth stages.

In the present study, fresh weight of all three species increased rapidly in the first 4 - 8 weeks of flush, probably due to elongation of the shoots. Gains in fresh weight after 8 weeks were minimal (Table 4). Gratkowski (1977) and McCavish (1980), working with ponderosa pine (*Pinus ponderosa* Laws.), found that this latter part of the growth phase involved developmental changes such as maturation of new shoot growth, increased cutinization of needles and accelerated formation of wood fibre in the tree. Similarly, Mayeux and Jordon (1981) showed that epicuticular wax content in golden weed (*Isocoma coronopifolia*) was two to four times higher during maturation stages than during the early growth phase of the plant.

Table 4. Changes in fresh weight of conifer plants over 4, 8 and 12 weeks under greenhouse and nursery conditions

| | Changes in fresh weight/plant (g) | | | |
|---|---|---|---|---|
| | Weeks after flush | | | |
| | (Greenhouse) | | | (Outdoor nursery) |
| Species | 4 | 8 | 12 | |
| Douglas-fir | 18.272 | 18.458 | 21.730 | 21.870 |
| Sitka spruce | 20.620 | 53.336 | 50.541 | 47.271 |
| Western red cedar | 6.910 | 8.970 | 9.086 | 10.100 |

It is reasonable to assume that western conifer species also undergo similar morphological and physiological changes during this 4-12 week growth and maturation phase. Glyphosate is very mobile in forest weeds (Prasad 1984a), and once it enters the deciduous plants it translocates and accumulates in the meristemic tissues. Deposition of epicuticular waxes and cutin in conifer needles provide a barrier to penetration of herbicides in conifers.

In conclusion, greenhouse and nursery studies using three species of western conifer suggest that "hardening" of needles is essential for establishing resistance/tolerance against the action of glyphosate. Needles of conifer seedlings undergo morphological and physiological changes during growth and maturation over a period of 4-12 weeks. Based on the information at hand it is recommended that a minimum period of 12 weeks from the onset of bud-flush be allowed before glyphosate is applied to a coniferous forest for successful weed control without significant damage to the crop species.

## ACKNOWLEDGMENTS

The author is grateful to Dal Travnick, John Studens and summer students for completion of this research and to Leo Cadogan for technical advice.

## REFERENCES

Cadogan, B.L., B.F. Zylstra, G. Nystrom, L.B. Pollock and P.M. Ebling. 1986. Spray deposit and drop size spectra from a high wing monoplane fitted with rotary atomizers. Trans Am. Soc. Agric. Eng. 29(2):402-406.

Duncan, D.B. 1955. Multiple range and multiple F tests. Biometrics 11:1-42.

Gratkowski, H.J. 1977. Seasonal effects of phenoxy herbicides on Ponderosa pine and associated brush species. Forest Sci. 23(1):212.

Hallett, R. 1985. Weed Control in Forest Nursery. Proceedings of the Canadian Forest Nursery Workshop. Fredericton, N.B. p. 46.

King, S.P. and S.R. Radosevich. 1985. Herbicide tolerance in relation to growth and stress in conifers. Weed Sci. 33:472-478.

Lund-Hoie, K. 1985. The herbicide glyphosate pp. 328-338 In "Glyphosate". Butterworth & Co., U.K.

Martin, J.P. and B. Juniper. 1975. Cuticles of Plants. Oxford Univ. Press. 451 p.

Mayeux, H.S. and W.R. Jordon. 1981. Epicuticular wax content and herbicide penetration of golden weed leaves. Proc. South Weed Sci. Soc. 20:389-393.

McCavish, W.J. 1980. Herbicide for woody weed control by foliar application. Proc. British Crop Protec. Conf. Weeds: 724-737.

McCormack, M.L., E.E. Sprague, T.B. Saviello, and R.J. Hendler. 1981. Timing of glyphosate and triclopyr treatments on forest brush. Proc. N.E. Weed Sci. Soc. 36:209-214.

Monsanto Canada Inc. 1982. Roundup-herbicide formulation of isopropyl amine salt of glyphosate post-emergent herbicide. Tech. Bull. Mon. 0573-2-73. 7 p.

Newton, M. 1977. Silvicultural applications of glyphosate. Roundup Forestry Seminar, Seattle, Washington.

Prasad, R. 1984a. Translocation of glyphosate in forest weeds. Plant Physiol. 77(4):152 Suppl.

Prasad, R. 1984b. Evaluation of Some Herbicides for Weed Control in Red Pine Plantations. Res. Rept. Expt. Comm. Weeds East, Quebec. p. 616-618.

Prasad, R. and B.L. Cadogan. 1987. Influence of small droplets on herbicide efficacy. Proc. ACAFA Symposium, Ottawa. pp. 1-12.

Radosevich, S.R., E.J. Roncoroni, S.C. Conrad, and W.B. McHenry. 1980. Seasonal tolerance of six coniferous species to eight foliage active herbicides. For. Service Publ. No. 26-1:3-9.

Reynolds, P.E., K. King, P. Whitehead, and T.S. MacKay. 1986. One-year results for a coastal British Columbia Glyphosate Conifer Release Trial. Proc. West. Soc. Weed Sci. 39:107-117.

Sutton, R.F. 1978. Glyphosate herbicide: an assessment of forestry potential. For. Chron. 54:24-28.

Sutton, R.F. 1984. Plantation establishment in boreal forests: glyphosate, hexazinone and manual weed control. For. Chron. Oct: 283-287.

Willis, R., R.A. Fletcher, G.R. Stephenson, G.R. and R. Prasad. 1987. Seasonal variation in conifer tolerance to glyphosate and triclopyr. Res. Rept. Expt. Comm. Weeds (East) Toronto. 667-668.

Wood, J.R. and R.C. Campbell. 1984. Glyphosate for conifer site preparation and release. Res. Rep. Expt. Comm. Weeds (East):455-456.

# COMPARATIVE CHANGES IN CONCENTRATION OF DISSOLVED IONS IN THE STREAM FOLLOWING LOGGING, SLASH BURNING, AND HERBICIDE APPLICATION (glyphosate) AT CARNATION CREEK, BRITISH COLUMBIA

J. Charles Scrivener
Department of Fisheries and Oceans
Biological Sciences Branch
Pacific Biological Station
Nanaimo, British Columbia V9R 5K6

## ABSTRACT

The patterns of dissolved ions were studied in the main channel, in two pristine tributaries, and in two tributary swamps (1600-trib, 2600-trib) for 14 yr prior to and for 2 yr after aerial applications of the herbicide ROUNDUP (glyphosate). Four percent (41.7 ha) of the main watershed and half of the watershed including the stream channel of tributary 1600 were sprayed with the herbicide. In all the streams electrical conductivity and the concentration of dissolved nitrate-N were negatively correlated with stream flow. After herbicide treatment these values were unchanged at minimum to median stream flow, but conductivity increased 21% and nitrate concentrations increased 3-fold during periods of freshet. Increases that were 4 times as large had been observed when these watersheds were logged and the logging slash was burned. Phosphate-P concentration was not correlated with stream flow and it increased 2-fold after herbicide application. No changes in dissolved phosphate concentration had been observed after logging and slash burning.

## INTRODUCTION AND METHODS

This paper describes the patterns of dissolved ions at the main flow guaging weir (B), three control sites (C-weir, E-weir, 2600-trib.), and a treated site (1600-trib.) for 14 yr prior to and for 2 yr after aerial applications of herbicide. During September 6-15, 1984, 2.118 kg/ha of ROUNDUP (glyphosate) was applied to 41.7 ha of Carnation Creek watershed with a Bell-47 helicopter and 7.9 m long MICROFOIL BOOM (Reynolds et al. 1989). Tributary 1600 and half of its watershed (4 ha) were sprayed. Tributary 1600 had been logged between January and May and logging slash was broad-cast burned on September 28 of 1977. Tributary 2600 was logged between January and May and the slash burned on September 14 of 1979. Tributaries C and E remained unlogged during the study. Earlier reports contained the complete study design and forestry plan (Dryburgh 1982; Scrivener 1988a).

Water samples were collected monthly from C-weir and E-weir and twice a month from B-weir between July 1971 and September 1986. After March 1984, they were collected monthly from tributaries 1600 and 2600. Samples were also obtained from tributary 1600 at less regular intervals during 1976, 1977, and 1978. Analyses for pH, alkalinity, and electrical conductivity were done in the field. In addition, water was frozen in polyethylene and acid washed glass bottles and transported to the chemistry laboratories at PBS and West Vancouver, where analyses for 16 other ions were completed. Analysis techniques were reported earlier (Scrivener 1975, 1982). Results are reported by water-year which began (October 1) and ended (September 30) during the annual period of minimum stream flow.

## RESULTS AND DISCUSSION

### Changes Among Dominant Ions

Pre-herbicide treatment years

A seasonal pattern of pronounced concentration peaks in summer and autumn and minima in winter and early spring was observed for the dominant cations (calcium, sodium, magnesium; positively charged) and anions (bicarbonate, silicate; negatively charged) that were dissolved in the stream (Scrivener 1975). Lower concentrations also occurred during months of high stream discharge, while higher values occurred during summer or autumn low flows (Scrivener 1982). Their concentrations were lower than those observed in pristine U.S. streams (Brown et al. 1973; Likens et al. 1970; Vitousek 1977), but they were similar to those in another cedar-hemlock forest in British Columbia (Feller 1977). Weathering of bedrock was the usual source of these ions (Likens et al. 1977; Bormann and Likens 1979).

Concentrations of the dominant ions appeared very flow regulated at Carnation Creek. Electrical conductivity, an indicator of the quantity of ions, was inversely related to stream flow at all sites in the Carnation Watershed (Scrivener 1975, 1982). In the main stream, the greatest conductivities occurred during water-years 1978-79 and 1979-80 after logging and slash burning were begun (Fig. 1). Conductivity was also inversely related to stream flow during individual freshets. If these storms occurred after long dry periods, then conductivities tended to be greater than for the whole water-year, but if they occurred during a period of frequent storms, conductivities were lower (Scrivener 1982, 1988b). Ion concentrations were not as flow regulated in either Hubbard Brook, New Hampshire (Likens et al. 1977) or Alsea River, Oregon (Brown et al. 1973), where logging and herbicide impacts were also studied.

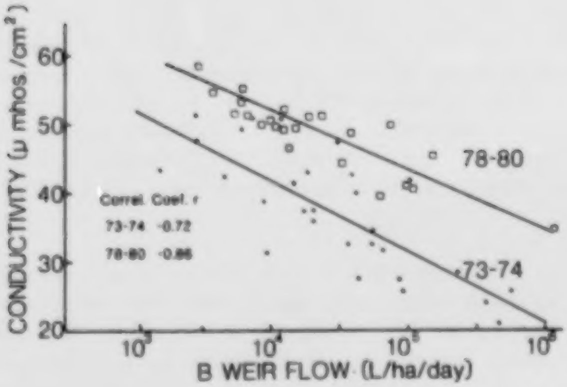


Figure 1. Relationships of stream conductivity and discharge measured at B-weir for October 1, 1973 to September 30,1974 and October 1,1978 to September 30,1980 at Carnation Creek. Dots represent samples from 1973-74, while squares are samples from 1978-80.

Pre-herbicide impacts of logging and other silvicultural practises on conductivity at Carnation Creek can be summarized in five points (Scrivener 1988b). They can be illustrated with plots through time of annual relationships between stream flow and conductivity (Fig. 2), and with plots of specific water-years at intensively logged sites (Fig. 3).

1. The impacts were modest with a maximum increase of 90% at high flows only in the most intensively logged and burned watersheds (Fig. 3). A maximum increase of 50% occurred in the main stream during high flows (B-weir, Fig. 2).

2. Conductivity increases were restricted to high or moderate flow levels. Little or no increase was observed at low flows during the summer (Figs. 2 and 3).

3. Increases occurred within a year of the commencement of logging and slash burning in each watershed.

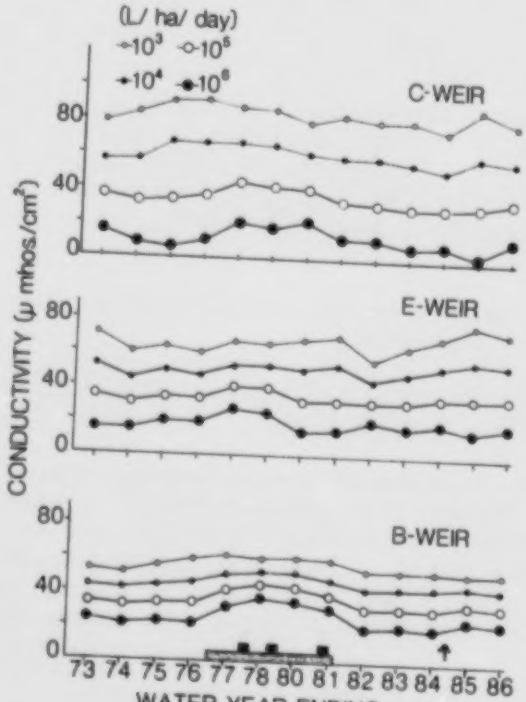


Figure 2. Changes of conductivity in the main stream (B) and in two undisturbed tributaries (C and E) during 16 yr of the Carnation Creek watershed study. Conductivities were calculated at high (large dots), medium high (large circles), medium low (small dots), and low discharges (small circles) from annual relationships between conductivity and stream flow. Periods of logging (shaded bar), slash burning (solid bars), and herbicide application (arrow) are also shown.

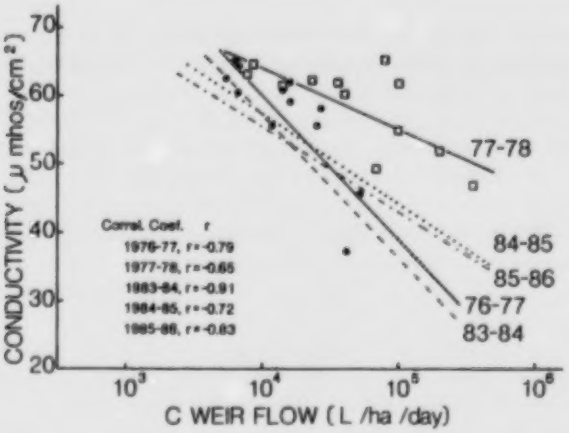


Figure 3. Relationships observed between electrical conductivity of water in tributary 1600 and stream flow during five water-years. Dots represent values from 1976-77, while squares are values from 1977-78. Conductivities between 1983 and 1986 are not shown here to maintain readability of the figure. Logging slash was burned at the end of 1976-77, while herbicide was applied at the end of 1983-84.

4. Electrical conductivity appeared to return to prelogging levels within 2 yr after forest harvesting had ceased in the watersheds (Fig. 2).

5. Stream conductivity might increase from and return to prelogging levels at a slower rate if logging slash was not burned (Scrivener 1988b).

Only small changes in the conductivity of stream water were observed in tributaries C and E, the untreated controls. The slope of the relationship between conductivity and stream flow changed only slightly from year to year as indicated by divergence and convergence of the points representing low to high flows (Fig. 2). A slight increase appeared for high flows during 1976-77 and 1977-78 at both sites. This may have been caused by the reduced number of storms and lower precipitation during these two water-years (Hetherington 1982; Scrivener 1982).

Post-herbicide treatment years

The inverse relationships between electrical conductivity and stream flow persisted after the herbicide treatment (Table 1), but they differed for treated and untreated sites. Untreated sites (C-weir, 2600-trib) were unchanged during water-years 1983-84, 1984-85 and 1985-86. The relationships tended to differ in slope and intercept among the years at the treated sites (B-weir, 1600-trib; Table 1). Conductivities were greater after the herbicide was applied, but only at high flows (Fig. 4). Although these changes were significant, they were not as great as those observed immediately after logging and slash burning (Figs. 2 and 3).

Table 1. Conductivity and stream flow were related for B-weir, C-weir, 1600 tributary, and 2600 tributary during water-years 1983-84, 1984-85 and 1985-86. Stream flows were not measured at 1600 and 2600, so flows from the watershed between these two sites (C-weir) were used for these sites

| Site | Water year | Relationship with flow |  |  | Comparison of intercepts |  |
|---|---|---|---|---|---|---|
|  |  | r | no. samples | probability | between years | all years |
| B-weir | 1983-84 | -0.93 | 25 | < 0.001 | F = 2.90<br>p = 0.06 |  |
|  | 1984-85 | -0.82 | 25 | < 0.001 |  | F = 2.10 |
|  | 1985-86 | -0.92 | 24 | < 0.001 | F = 3.33<br>p = 0.04 | p = 0.09 |
| C-weir | 1983-84 | -0.92 | 13 | < 0.001 |  |  |
|  | 1984-85 | -0.79 | 14 | < 0.001 |  | F = 0.81 |
|  | 1985-86 | -0.82 | 12 | < 0.01 |  | p = 0.53 |
| 1600 trib | 1983-84 | -0.91 | 9 | < 0.001 | F = 2.56<br>p = 0.10 |  |
|  | 1984-85 | -0.72 | 13 | < 0.01 |  | F = 2.17 |
|  | 1985-86 | -0.83 | 13 | < 0.001 | F = 3.36<br>p = 0.05 | p = 0.09 |
| 2600 trib | 1983-84 | -0.95 | 7 | < 0.01 |  |  |
|  | 1984-85 | -0.78 | 13 | < 0.01 |  | F = 1.70 |
|  | 1985-86 | -0.85 | 12 | < 0.001 |  | p = 0.18 |

At Hubbard Brook, New Hampshire, losses of dissolved substances increased ~10 times when the forest was cut and the area treated with herbicide for two succeeding years (2,4,5-T; Bormann et al. 1974). These changes persisted for a number of years. At Carnation Creek, small changes were observed for only one or both of the post-herbicide years.

## Changes Among Stream Nutrients

### Pre-herbicide treatment years

Like other dominant ions, nitrate concentration was inversely related to stream flow during each water-year, but nitrates were flushed from the watershed during the first autumn storms (Scrivener 1982). Nitrate concentrations were either unrelated to flow (prelogging) or they became positively related to flow (post-burning) during these storms (Fig. 5). Unlike many

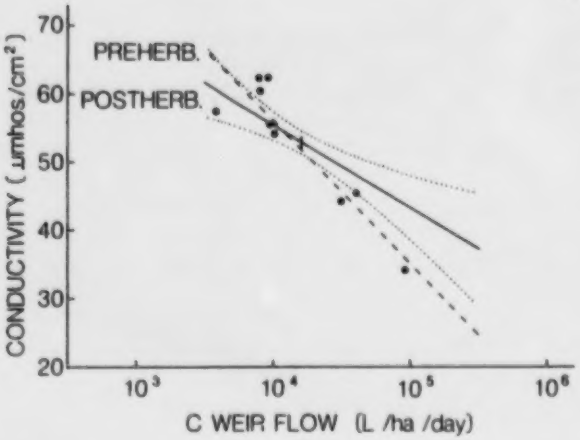


Figure 4. Relationships obtained between electrical conductivity of tributary 1600 and stream flow during the water-year prior to application of herbicide (dots, dash line), and during the post-herbicide period (1984-86, solid line). Confidence limits (dotted lines) are shown for the post-herbicide relationship.

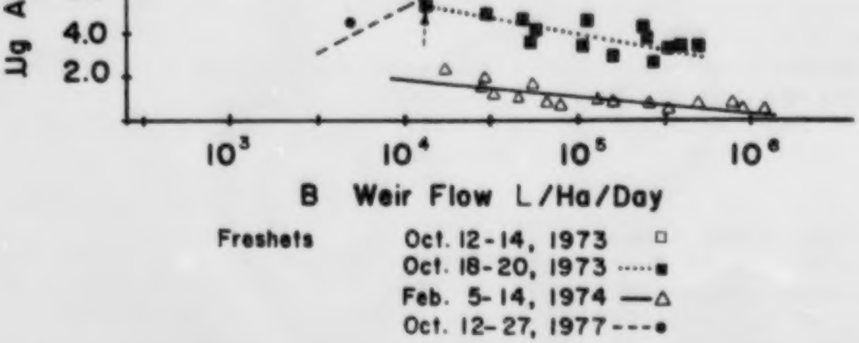


Figure 5. Relationships observed for nitrate-N concentrations versus stream flow during 4 freshets in Carnation Creek. Arrows indicate concentrations at the beginning of the October 12-14, 1973 (solid) and of the October 18-20, 1973 (stippled) freshets. Burning of logging slash occurred on September 28, 1977.

dominant ions, nitrate typically originates from input in precipitation, from "nitrogen fixation" by bacteria on the roots of vegetation (atmospheric nitrogen converted to nitrate in the soil), and from rotting vegetation in the soils (Bormann and Likens 1979; Vitousek et al. 1982). Therefore soil and vegetation cover types may influence nitrate availability to the stream.

Pre-herbicide impacts of logging and other silvicultural practises on nitrate concentrations in the stream can be summarized in four points.

1. Nitrate-N concentrations increased ~7 times in tributary 1600 (Fig. 6), which was intensively logged and burned, while nitrate increased ~2 times in Carnation Creek (Fig. 7). Nitrates increased ~10 times at Hubbard Brook (Bormann et al. 1974) and ~5 times at Alsea River (Brown et al. 1973), when watersheds were deforested.
2. The first impacts occurred a year after logging was begun (Figs. 6 and 7).
3. Unlike conductivity, nitrate concentrations increased over the full range of stream flow following logging and burning.
4. Increases of nitrates continued for 7 yr at high flows, but for only 2 yr at low flows (Fig. 7). Nitrate concentrations returned to prelogging levels within 3 yr of the termination of logging and slash burning activities at Carnation Creek. Nitrates were at prelogging levels at all sites by 1984, when the herbicide was applied (Figs. 6 and 7).

In tributary E, a control site, nitrate concentrations were variable, but no trend was apparent during 16 yr of monitoring. Differences in concentration between high and low flows were reduced during 1976-77 and 1977-78, which were years with less precipitation and fewer storms (Fig. 7). The greatest range of concentrations occurred during 1980-81, a wet year with frequent storms. This divergent and convergent pattern in range of concentrations was also observed, but it was less pronounced in the main stream (B; Fig. 7).

Nitrate-N concentrations in tributary 1600 approached levels that produce mortalities among salmonid eggs. In laboratory studies, steelhead trout eggs incubating in very soft water (hardness ~20 mg/L) were susceptible to nitrate toxicity at 80 $\mu$g at./L nitrate-N (Kincheloe et al. 1979). More nitrate (160 $\mu$g at./L nitrate-N) was required to produce similar mortalities among cutthroat trout and chinook salmon eggs, and coho salmon were more resistant. The minimum level of nitrate that effects chum salmon eggs is unknown. Carnation Creek water is softer than water in the reported study (hardness ~10 mg/L; Scrivener 1975) and after slash burning in 1600 watershed nitrate-N concentrations peaked at 60 $\mu$g at./L with a mean of 25 $\mu$g at./L (Fig.5, 1977-78). Nitrates would probably never reach toxic levels unless a majority of a watershed area was burned in a single year.

Concentrations of phosphate-P, another nutrient, were very low throughout the study and they were unrelated to stream flow (Scrivener 1975, 1982). No seasonal pattern was observed for this ion. Concentrations of total dissolved phosphate-P remained unchanged in the main stream during the period of logging and slash burning (Fig. 8). However, during this period the higher concentrations of phosphate occurred in samples that were collected immediately after burns (Scrivener 1982). Phosphate concentrations were also unchanged during 15 yr of study in the Alsea watershed (Brown et al. 1973).

In the intensively logged and burned tributaries, phosphate concentrations increased. This occurred immediately after the burning of logging slash and persisted for at least 1 yr (Table 2). Phosphate concentrations had returned to prelogging levels prior to herbicide application in 1984 (Table 2).

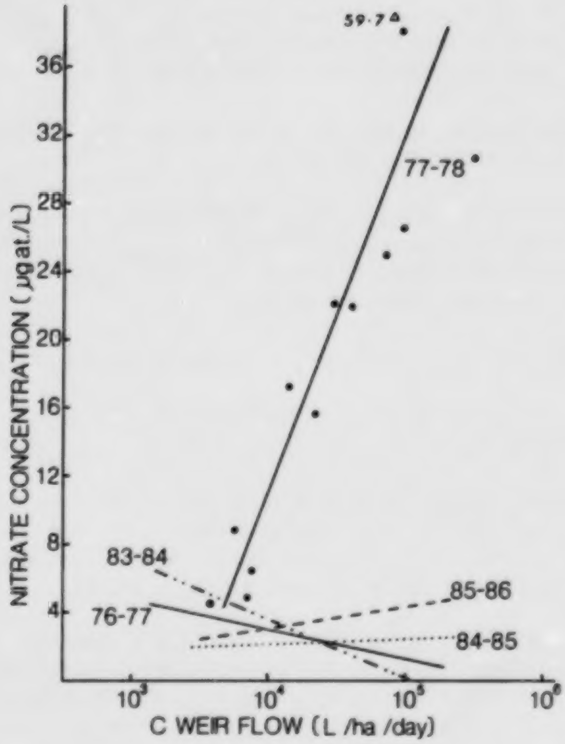


Figure 6. Relationships of nitrate-N concentrations and stream flow from tributary 1600 water samples taken during five water-years. C-weir flows were used because stream flow was not measured in tributary 1600. Concentrations for 1977-78 only are shown (dots, triangle) so that figure readability is preserved. Logging slash was burned at the end of 1976-77, while herbicide was applied at the end of 1983-84. Lines for 1984-85 and 1985-86 were calculated, but their slopes were not significantly greater than zero.

Post-herbicide treatment years

Nitrate concentrations also increased after ROUNDUP (glyphosate) was applied at Carnation Creek. The relationships between concentration and flow were evident at the control sites and in the main stream (B), but they were not significant for 1600 tributary (Table 3). The slope of a line fitted to the points was zero or slightly positive for 1984-85 and 1985-86 (Fig. 6). During both years, more dissolved nitrate was present in 1600 tributary at high stream flows. Despite the significant increase, nitrate concentrations were only one quarter of those obtained immediately after slash burning and they did not approach levels that are toxic to incubating salmonid eggs (Kincheloe et al. 1979). In the main stream, the relationship between nitrate and stream flow did not change significantly, but it did weaken during 1984-85 (Table 3). The highest nitrate concentrations were also obtained in the year following herbicide treatment.

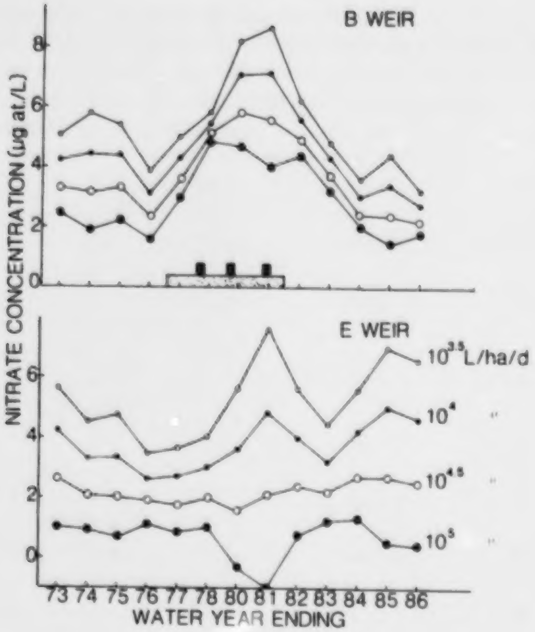


Figure 7. Nitrate-N concentrations in the main stream (B) and an undisturbed tributary (E) during the Carnation Creek study. They were calculated from annual relationships between nitrate and stream flow at 4 discharges. Bars indicate periods of logging (shaded) and slash burning (solid).

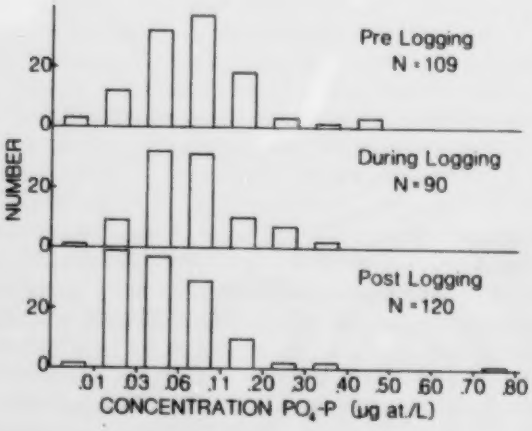


Figure 8. Phosphate-P concentrations observed in Carnation Creek during prelogging, forest harvesting, and post harvesting phases of the study (B-weir).

Table 2. Concentrations of total dissolved phosphate-P at B-weir, 1600 tributary and 2600 tributary by water-year (October 1 to September 30)

| Site | Water-year | Mean concentration $PO_4$-P (µg at./L) | No. samples | Comparisons | |
|---|---|---|---|---|---|
| B-weir | 1983-84 | 0.039 | 25 | | t = 2.26 |
| | 1984-85 | 0.080 | 25 | | p = 0.03 |
| | 1985-86 | 0.103 | 24 | | |
| 1600 trib | 1976-77 | 0.071 | 13 | t = 2.37<br>p = 0.03 | |
| | 1977-78 | 0.150 | 12 | | |
| | 1983-84 | 0.083 | 9 | t = 1.82<br>p = 0.08 | t = 2.10<br>p = 0.05 |
| | 1984-85 | 0.140 | 13 | t = 1.60<br>p = 0.12 | |
| | 1985-86 | 0.122 | 13 | | |
| 2600 trib | 1983-84 | 0.092 | 7 | | |
| | 1984-85 | 0.114 | 13 | | t = 1.22<br>p = 0.24 |
| | 1985-86 | 0.127 | 12 | | |

At Hubbard Brook, nitrate levels in the stream increased 40-fold in the first year and 56-fold in the second year after use of herbicides (Likens et al. 1970). They subsequently began declining, but elevated nitrate values persisted for more than 5 yr. In a University of British Columbia research forest stream, nitrate concentrations increased 7-fold after use of glyphosate and elevated levels persisted for 2 yr (Kimmins et al. 1989). The additional nitrate came from accelerated rates of nitrification (atmospheric nitrogen converted to nitrate) and of decomposition (organic matter), from reduced nitrogen uptake by vegetation and from acidification of cation exchange sites in the soil (Bormann et al. 1974; Vitousek et al. 1982). It was leached by water that was passing through the soil to the stream.

Changes in nitrate concentrations in Carnation Creek were smaller and they persisted for a shorter time when compared to other watersheds. This probably occurred because the soils were already very acidic (Oswald 1973) and because nitrate tends to be immobilized in the organic layer of soils in Pacific northwest forests (Vitousek et al. 1982). Thus only smaller quantities of nitrate could be leached from these soils.

Table 3. Relationships obtained between nitrate-N concentration and stream flow at B-weir, C-weir, 1600 tributary, and 2600 tributary for water-years 1983-84, 1984-85 and 1985-86. Steam flows were not measured at sites 1600 and 2600, so flows from the watershed between these two sites (C-weir) were used

| | | Relationship with flow | | | |
|---|---|---|---|---|---|
| Site | Water-year | r | no. samples | probability | Comparison of intercepts for all years |
| B-weir | 1983-84 | -0.51 | 25 | < 0.01 | F = 0.60 |
| | 1984-85 | -0.46 | 25 | < 0.05 | p = 0.62 |
| | 1985-86 | -0.55 | 24 | < 0.01 | |
| C-weir | 1983-84 | -0.72 | 13 | < 0.01 | F = 1.03 |
| | 1984-85 | -0.81 | 14 | < 0.001 | p = 0.41 |
| | 1985-86 | -0.63 | 12 | < 0.05 | |
| 1600 trib | 1983-84 | -0.61 | 9 | < 0.09 | F = 3.30 |
| | 1984-85 | 0.07 | 13 | < 0.82 | p = 0.06 |
| | 1985-86 | -0.21 | 13 | < 0.50 | |
| 2600 trib | 1983-84 | -0.85 | 7 | < 0.05 | F = 1.08 |
| | 1984-85 | -0.16 | 13 | < 0.55 | p = 0.39 |
| | 1985-86 | -0.90 | 12 | < 0.001 | |

Changes in concentration of dissolved phosphate were greater than or equal to those observed after logging and slash burning. Total dissolved phosphate-P increased 2-fold during 1984-85 and 3-fold during 1985-86 in the main stream (B, Table 2). Despite this apparent change, mean phosphate concentrations were within the range that was observed during the prelogging and logging periods (Fig. 8). Phosphate-P levels appeared to decline slowly after logging and slash burning, but increased to the highest mean levels after the application of herbicide. In the treated tributary, phosphate levels increased 2-fold after slash burning, they had decreased by 1983-84 and then increased to similar levels again after the herbicide treatment (1600, Table 2). Phosphate concentrations were unchanged in control watersheds between 1983 and 1986. At C-weir values ranged from less than 0.02 to 0.30 $\mu$g at./L during water-years 1983-84, 1984-85 and 1985-86. Differences between watersheds B, C, E, 1600, and 2600 (spatial variability) were ~70% of the increase in phosphate concentrations that was attributed to the application of herbicide (Table 2).

Phosphorus tends to be strongly conserved in forest ecosystems. Inputs of dissolved phosphate to a watershed (precipitation) were 2-3 times the dissolved outputs in the stream (Likens et al. 1977). This was similar to observed results at Carnation Creek (Scrivener 1975). Phosphate concentrations doubled when the precipitation reached the soil after washing the vegetation canopy, but only 20% of the dissolved phosphate reached the stream (Feller 1977; Scrivener 1975). This was only a miniscule part of the total phosphorus that was cycling between the vegetation and soils. For example, the annual leaf litter fall at Hubbard Brook contained 1,900 g P/ha, while 100 g P/ha entered in precipitation and 21 g P/ha exited in the stream (Hobbie and Likens 1973).

It is unlikely that much of the additional phosphate in the stream came from the herbicide, although the formulation of ROUNDUP contained phosphate. Phosphate concentrations in stream water at Hubbard Brook also increased 2-3 fold (Hobbie and Likens 1973), even though the herbicides that were used there (Bromacil; 2,4,5-T; Bormann et al. 1974) did not contain phosphate. Therefore dissolved phosphate in both streams probably came from vegetation that was killed by the herbicides.

Annual variability of inputs and decomposition of litter determined the amount of phosphate that could be leached by water passing through the soil to the stream (Likens et al. 1977). After logging, litter consisted of coniferous slash of low phosphorus content (Duvigneaud and Denaeyer-de Smet 1970). Much of this phosphorus was probably lost to the atmosphere as ash when the slash was burned (Lloyd 1971; Lewis 1974). Therefore, only a slight increase in phosphate was observed in Carnation Creek. Later, phosphate was released from the vegetation that was killed by ROUNDUP, which targeted the new deciduous vegetation (richer in phosphorus, Duvigneaud and Denaeyer-de Smet 1970). More phosphate was leached because this richer source was not lost to burning.

The majority of phosphorus transported by streams is usually attached to particulate matter and not dissolved phosphate (Likens et al. 1977). This is probably the major transport route of phosphorus in Carnation Creek, but unlike other watersheds the transport of suspended particles did not increase in Carnation Creek after logging and slash-burning (Scrivener and Brownlee 1989). Therefore losses of particulate phosphorus probably did not increase significantly, but they were not measured. Particulate phosphorus that is being transported in the stream is of no use to this ecosystem unless it becomes trapped and decomposes in the bed.

## MANAGEMENT IMPLICATIONS AND CONCLUSIONS

Removal of vegetation, disturbance of soils, and burning of logging slash released more ions and nutrients that were leached from the soil by water passing through it to the stream. Within a 1 or 2-yr period, the additional ions had been leached from the soil and the concentrations of ions in the stream had returned to levels that were similar to prelogging conditions. The application of herbicide again caused an increased release of ions and nutrients, but it was of a smaller magnitude, except for dissolved phosphate. Herbicide effects on this ion were of a greater or similar magnitude to those of logging and burning. These impacts tended to be smaller in magnitude and shorter in duration than those reported for other watersheds.

Undisturbed stream ecosystems depend on inputs of leaves from deciduous trees (alder) and of needles from conifers on the stream banks. This detritus becomes trapped in the substrate and forms the basis of the food chain (Kaushik and Hynes 1968; Neaves 1978). Low light intensities under the canopy, and low nutrients and high scouring in the stream make algal production a minor source of energy for stream production (Shortreed and Stockner 1982).

Clearcutting of the forest greatly reduces detritus inputs, but it increases light intensities, nutrients and algal production in streams (Murphy and Hall 1981). Algal production did not increase significantly in Carnation Creek after logging and slash burning because low dissolved phosphate values limited its production (Shortreed and Stockner 1982).

The application of herbicide would reduce the regeneration of deciduous vegetation, but it made more phosphate available for algal production in the stream.

## ACKNOWLEDGEMENTS

Assistance in the field by many individuals during the last 5 years is gratefully acknowledged, but Messrs. B.C. Andersen, S.G. Baillie and R.M. Leahy require a special thank you. Messrs. P. Kluckner, K. Stephens and members of the E.P.S. chemistry laboratory, West Vancouver made special contributions during analysis of the samples.

## REFERENCES

Bormann, F.H., G.E. Likens, T.G. Siccama, R.S. Pierce and J.S. Eaton. 1974. The export of nutrients and recovery of stable conditions following deforestation at Hubbard Brook. Ecol. Monogr. 44:255-277.

Bormann, F.H. and G.E. Likens. 1979. Pattern and Process in a Forested Ecosystem. Springer-Verlag, New York, NY, 253p.

Brown, G.W., A.R. Gahler and R.B. Marston. 1973. Nutrient losses after clear-cut logging and slashburning in the Oregon coast range. Water Resour. Res. 9:1450-1453.

Dryburgh, J.G. 1982. Carnation Creek logging and silvicultural treatment program, p.36-44. In: Hartman, G.F. (ed.) Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404p.

Duvigneaud, P. and S. Denaeyer-De Smet. 1970. Biological cycling of minerals in temperate deciduous forests, p. 199-225. In: D.E. Reichle (ed.) Analysis of temperate forest ecosystems. Springer-Verlag, New York, NY. 304 p.

Feller, M.C. 1977. Nutrient movement through western hemlock-western red cedar ecosystems in southwestern British Columbia. Ecology 58:1269-1283.

Hetherington, E.D. 1982. A first look at logging effects on the hydrologic regime of Carnation Creek experimental watershed, p.45-63. In: Hartman, G.F. (ed.) Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404p.

Hobbie, J.E. and G. E. Likens. 1973. Output of phosphorus, dissolved organic carbon and fine particulate carbon from Hubbard Brook watersheds. Limnol. Oceanogr. 18:734-742.

Kaushik, N.K. and H.B.N. Hynes. 1968. Experimental study on the role of autumn-shed leaves in aquatic environments. J. Ecol. 56:229-243.

Kimmins, J.P., K.M. Tsze and R.E. Bigley. 1989. Development of non-commercial vegetation following clearcutting and clearcutting-plus-slashburning and some biogeochemical effects of herbicidal control of this vegetation. This proceedings.

Kincheloe, J.W., G.A. Wedemeyer and D.L. Koch. 1979. Tolerance of developing salmonid eggs and fry to nitrate exposure. Bull. Environ. Contam. Toxic. 23:575-578.

Lewis, Jr., W.M. 1974. Effects of fire on nutrient movement in a South Carolina pine forest. Ecology 55:1120-1127.

Likens, G.F., F.H. Bormann, N.M. Johnson, D.W. Fisher and R.S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Monogr. 40:23-47.

Likens, G.F., F.H. Bormann, R.S. Pierce, J.S. Eaton and N.M. Johnson. 1977. Biogeochemistry of a forested ecosystem. Springer-Verlag, New York, NY, USA. 146p.

Lloyd, P.S. 1971. Effects of fire on the chemical status of herbaceous communities of the Derbeshire Dales. J. Ecol. 59:261-273.

Murphy, M.L. and J.D. Hall. 1981. Varied effect of clear-cut logging on predators and their habitat in small streams of the Cascade mountains. Can. J. Fish. Aquat. Sci. 38:137-145.

Neaves, P.I. 1978. Litter fall, export, decomposition, and retention in Carnation Creek, Vancouver Island. Fish. Mar. Serv. Tech. Rep. 809: 43p.

Oswald, E.T. 1973. Vegetation and soils of Carnation Creek watershed. Pac. For. Res. Cent., Can. For. Ser., Victoria, British Columbia, Int. Rep. 43: 38p.

Reynolds P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. Overview of Carnation Creek herbicide study: historical perspective, experimental protocols and spray operations. This proceedings.

Scrivener, J.C. 1975. Water, water chemistry and hydrochemical balance of dissolved ions in Carnation Creek watershed, Vancouver Island, July 1971-May 1974. Can. Fish. Mar. Ser. Tech. Rep. 564: 141p.

Scrivener, J.C. 1982. Logging impacts on the concentration patterns of dissolved ions in Carnation Creek, British Columbia, p.64-80. In G.F. Hartman (ed.) Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404p.

Scrivener, J.C. 1988a. The Carnation Creek experimental watershed project: a description and history from 1970 to 1986. p. 1-10. In T.W. Chamberlin (ed.) Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biological Station, Nanaimo, British Columbia. 239 p.

Scrivener, J.C. 1988b. Changes in the concentration of dissolved ions during 16 years at Carnation Creek, British Columbia, p. 75-80. In T.W. Chamberlin (ed.) Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biological Station, Nanaimo, British Columbia. 239 p.

Scrivener, J.C. and M.J. Brownlee. 1989. Effects of forest harvesting on spawning gravel quality and on incubation survival of chum (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) in Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. 46(4).

Shortreed, K.S. and J.G. Stockner. 1982. The impact of logging on periphyton biomass and species composition in Carnation Creek: a coastal rain-forest stream on Vancouver Island, British Columbia, p.197-209. In G.F. Hartman (ed.) Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404p.

Vitousek, P.M. 1977. The regulation of element concentrations in mountain streams in northeastern United States. Ecol. Monogr. 47:65-87.

Vitousek, P.M., J.R. Gos, C.C. Grier, J.M. Melillo and W.A. Reiners. 1982. A comparative analysis of potential nitrification and nitrate mobility in forest ecosystems. Ecol. Monogr. 52:155-177.

# CHANGES IN THE TEMPERATURE REGIME OF A VALLEY-BOTTOM TRIBUTARY OF CARNATION CREEK, BRITISH COLUMBIA, OVER-SPRAYED WITH THE HERBICIDE ROUNDUP[1] (GLYPHOSATE)

L. Blair Holtby
Biological Sciences Branch
Department of Fisheries and Oceans
Pacific Biological Station
Nanaimo, B.C. V9R 5K6

## ABSTRACT

The temperature of a valley-bottom tributary of Carnation Creek was monitored for 2 years following the aerial application of the herbicide ROUNDUP (glyphosate) to the riparian vegetation over the entire length of the tributary. Temperature changes were assessed by comparing water temperatures in the tributary with temperatures in the main-stem of Carnation Creek at a site immediately above the confluence of the main-stem and the tributary. Significant increases in mean daily temperatures of 0.7°C were observed during the summer following spraying. Daily maximum temperatures increased by 2.7°C in the first summer after spraying and by 1.4°C in the second summer. The increased temperatures observed after herbicide application were associated with the defoliation of riparian alder. Although no adverse effects of the temperature changes were observed on resident salmonids in the tributary, the additive effects of numerous herbicide treatments in a larger river could be of some concern, as would a similar treatment at a warmer site.

## INTRODUCTION

Temperature changes of 0.5-2°C, associated with the removal by logging of riparian vegetation have had significant effects on the salmonid fishes in Carnation Creek (Holtby 1988a, 1988b). The effects of temperature changes were seen primarily through shifts in the timing of life-history events such as fry emergence and smolt emigration. Fry emergence and smolt emigration are the culmination of developmental or maturational processes that extend over several months. Consequently, small changes in temperature can have large effects on the completion date of the process. For instance, temperature increases of less than 1°C during the late winter were associated with earlier fry emergence by as much as 6 weeks (Holtby 1988b).

Permanent tributaries, such as the one over-sprayed in this experiment, are important year-round rearing areas for juvenile salmon. Although abating to some extent, the increases in water temperature in the tributary that were caused by clear-cut logging of the site in the winter of 1976/77 are still present. My interest in the effects of herbicide treatment of riparian alder common around this site was largely motivated by concern over the adverse effects of further increases in tributary temperatures, particularly during the summer.

The purpose of this paper is to document temperature changes in a small tributary over-sprayed with the herbicide ROUNDUP (Reynolds et al. 1989) that have been observed up to 2 years after spraying.

---

[1] Registered trademark of Monsanto Corporation, St. Louis, MO.

## METHODS

Temperatures in the tributary at 1600 m ("1600T") and in the main-stem of Carnation Creek ("1600M") were continuously measured with Lambrecht 256 recorders. The temperature probe in 1600T was located in a small pool, near the confluence of the tributary and the main-stem (Fig. 1). The temperature probe in 1600M was in a similar small pool~50m upstream of the confluence with 1600T. Temperature records from both sites begin in May 1976, seven months before the first logging around the site.

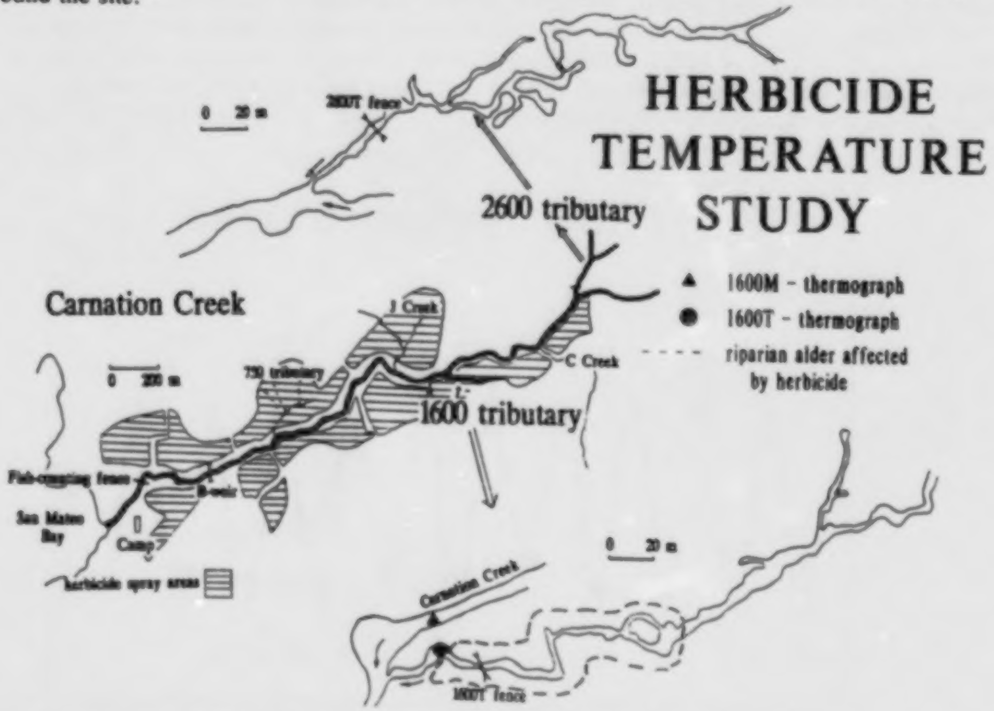

HERBICIDE
TEMPERATURE
STUDY
0 20 m
2600T fence
2600 tributary
Carnation Creek
J Creek
0 200 m
750 tributary
C Creek
1600 tributary
Fish-counting fence
B-weir
San Mateo Bay
Camp
herbicide spray areas ▤
▲ 1600M - thermograph
● 1600T - thermograph
- - - - riparian alder affected by herbicide
0 20 m
Carnation Creek
1600T fence

Figure 1. Sketch map of 1600T showing location of thermographs and approximate extent of riparian alder affected by herbicide.

Monthly charts were digitized, and temperature-time co-ordinates stored in a computer data-base. Field personnel manually recorded temperatures and times for the beginning and end of each monthly period which permitted linear corrections for instrument drift during digitizing. Temperature resolution was ±0.1°C while time resolution was ±15 min.

The effects of herbicide application on water temperatures were estimated using forward-stepping multiple regression of temperatures in 1600T, on temperatures in 1600M, and sets of dummy variables that indicated season and herbicide treatment. The mean temperatures used were weekly averages from October 1981 to December 1986. Minimum and maximum temperatures were the absolute minimums and maximums within the same weekly periods. All logging in the watershed was completed by June 1981. The temperatures were grouped into three seasons: spring (February-May); summer (June-September); and winter (October-January). There were six dummy variables corresponding to the three seasons and either one or two years after the herbicide application (September 1984). Finally, I assumed a simple stepped model of revegetation around 1600T. Complete revegetation to the point of canopy closure was assumed to take 15 years. Beginning in February and concluding at the end of October each year, the revegetation index was increased weekly by 0.00167 (1/15 yr/40 wk/yr). The index was held constant over each winter.

## RESULTS

The temperature record at 1600M and 1600T began in May 1976, just 7 months before logging at the site and an insufficient period of time to directly estimate logging effects. However, mean temperatures in 1600M and 1600T did increase substantially after logging (Fig. 2,3). The magnitude of the increases appear comparable to those observed at the main hydrological weir (Holtby 1988a): 2-3°C throughout April-October and 0.5-1.0°C in the winter. The temperature increases in 1600T were even greater, with mean summer temperatures increasing as much as 6.5°C 2-yr after logging (Fig. 2,3). One aspect of the temperature increases of particular significance is the accelerated warming of 1600T in the spring (February-May). It was temperature increases during this period that were associated with most of the logging impacts on the coho salmon (Holtby 1988b) and chum salmon (Scrivener 1988).

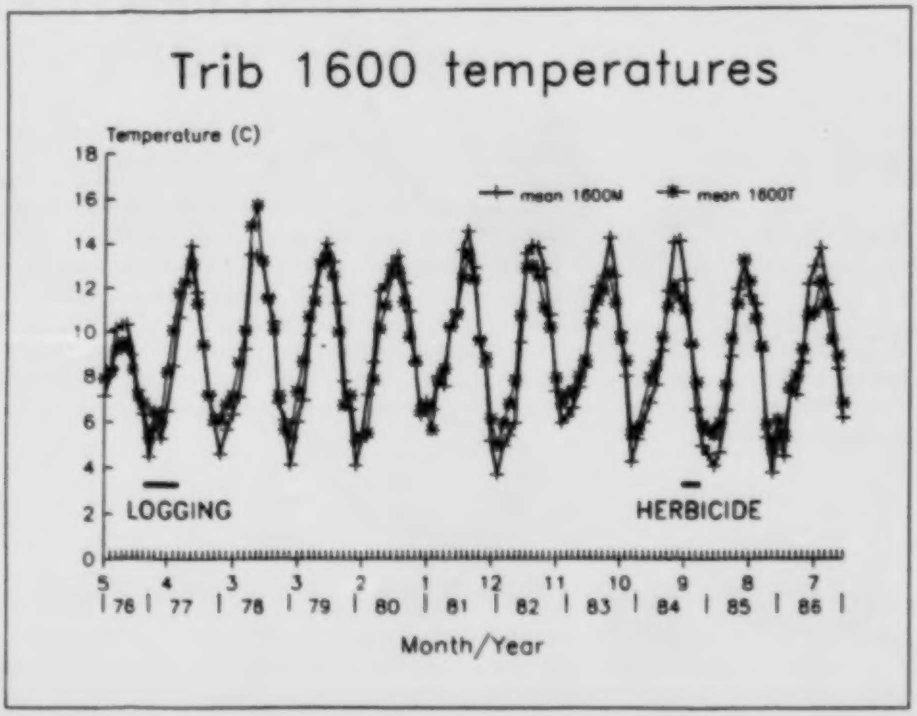


Figure 2. Mean monthly temperatures in 1600M and 1600T from May 1976-December 1986. Period of logging around 1600 m and herbicide application are shown.

The effects of logging on maximum temperatures in 1600M and 1600T were quite large: 2 yr after logging maximum temperatures during the summer (April-October) had increased by 5-12°C (Figs. 4,5). Note again the accelerated warming of 1600T in the spring (Fig. 4). Minimum temperatures during the summer were 0.5-2°C higher after logging (Figs. 6,7). Minimum temperatures in other months were not affected.

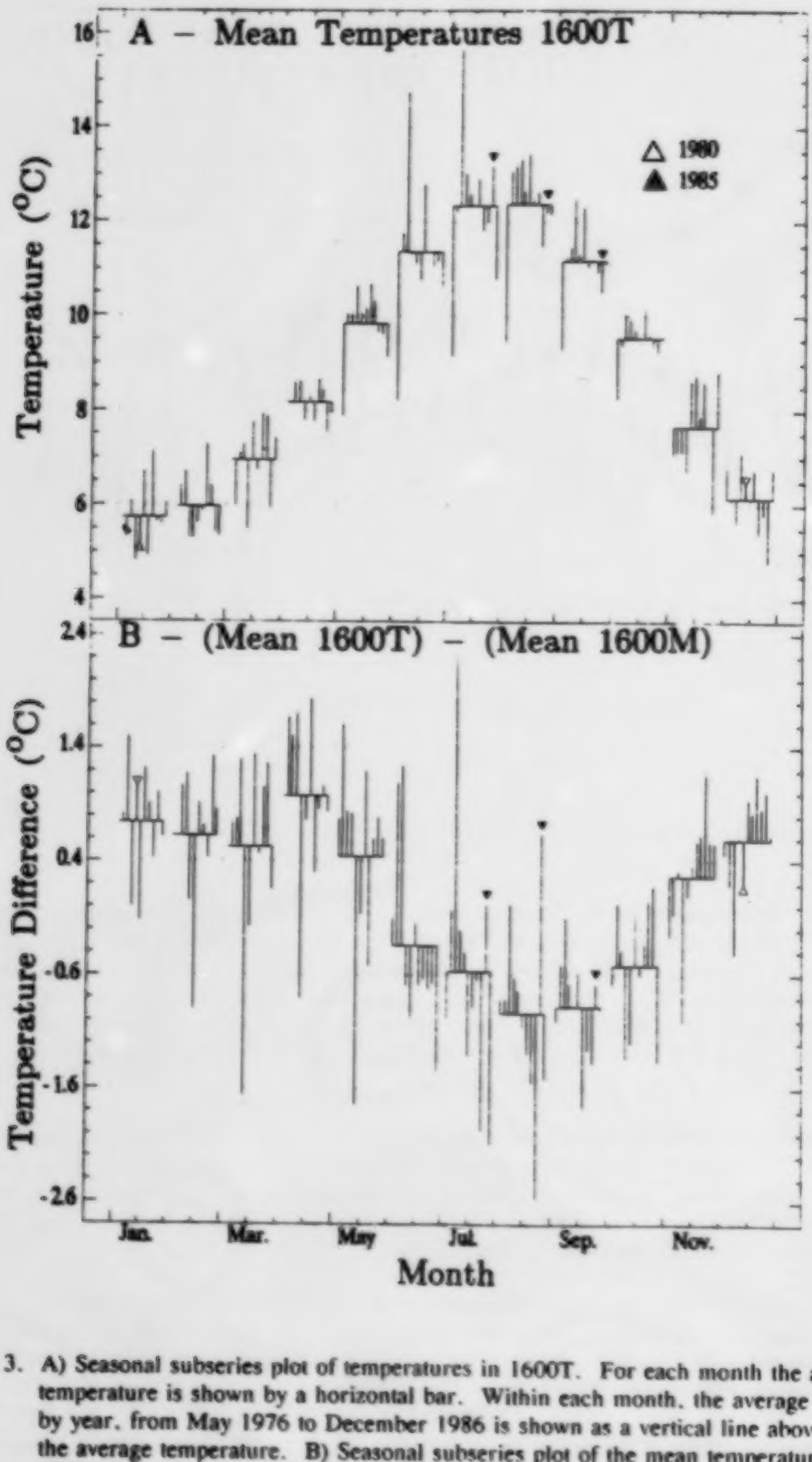


Figure 3. A) Seasonal subseries plot of temperatures in 1600T. For each month the average temperature is shown by a horizontal bar. Within each month, the average temperature by year, from May 1976 to December 1986 is shown as a vertical line above or below the average temperature. B) Seasonal subseries plot of the mean temperature difference between 1600T and 1600M from May 1976 to December 1986.

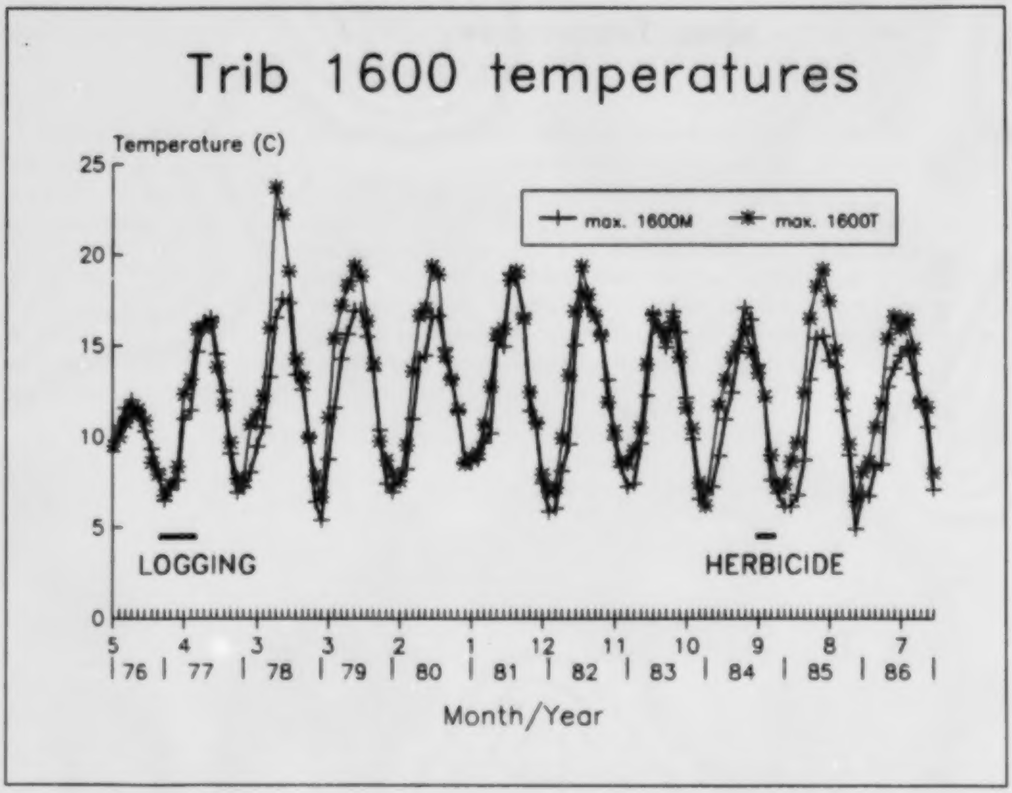


Figure 4. Mean maximum monthly temperatures in 1600M and 1600T from May 1976 to December 1986.

Herbicide was applied at 1600T 7.5 years after logging. At the time of treatment an alder canopy had nearly closed over the lower half of 1600T (Fig. 1). In response to the decreasing amounts of sunlight reaching 1600T, summer minimum, mean and maximum temperatures were returning to pre-logging values (Fig. 2-7). The return to pre-logging temperatures in 1600T would have been completed roughly 15-20 years after logging. Re-vegetation along the stream proper is a much slower process and there is no indication that temperatures at 1600M are returning to pre-logging values.

In the spring following herbicide application, the young alder around 1600T only partially leafed-out but a large number of trees had recovered sufficiently by 1986 to again provide some canopy over the lower half of the tributary. During the summer of 1985, temperatures in 1600T had increased to approximately the same levels seen 4-6 yr after logging. Temperature increases were particularly evident during July and August (Fig. 3,5,7).

By the summer of 1986, the temperature effect of the herbicide was waning. Mean temperatures during July and August, the months during which apparent herbicide effects had been greatest, had returned to levels similar to those observed in the summer before spraying (Fig. 2,3). It would appear that the herbicide set alder development back by only 1-2 years.

The quantitative effects of the herbicide on temperatures in 1600T were estimated using multiple regression. Statistically significant effects on mean temperatures were detected only during the first summer (Table 1), consistent with the graphical analysis described above. In the first summer after spraying, mean summer temperatures increased by 0.75° (Table 1). Observations

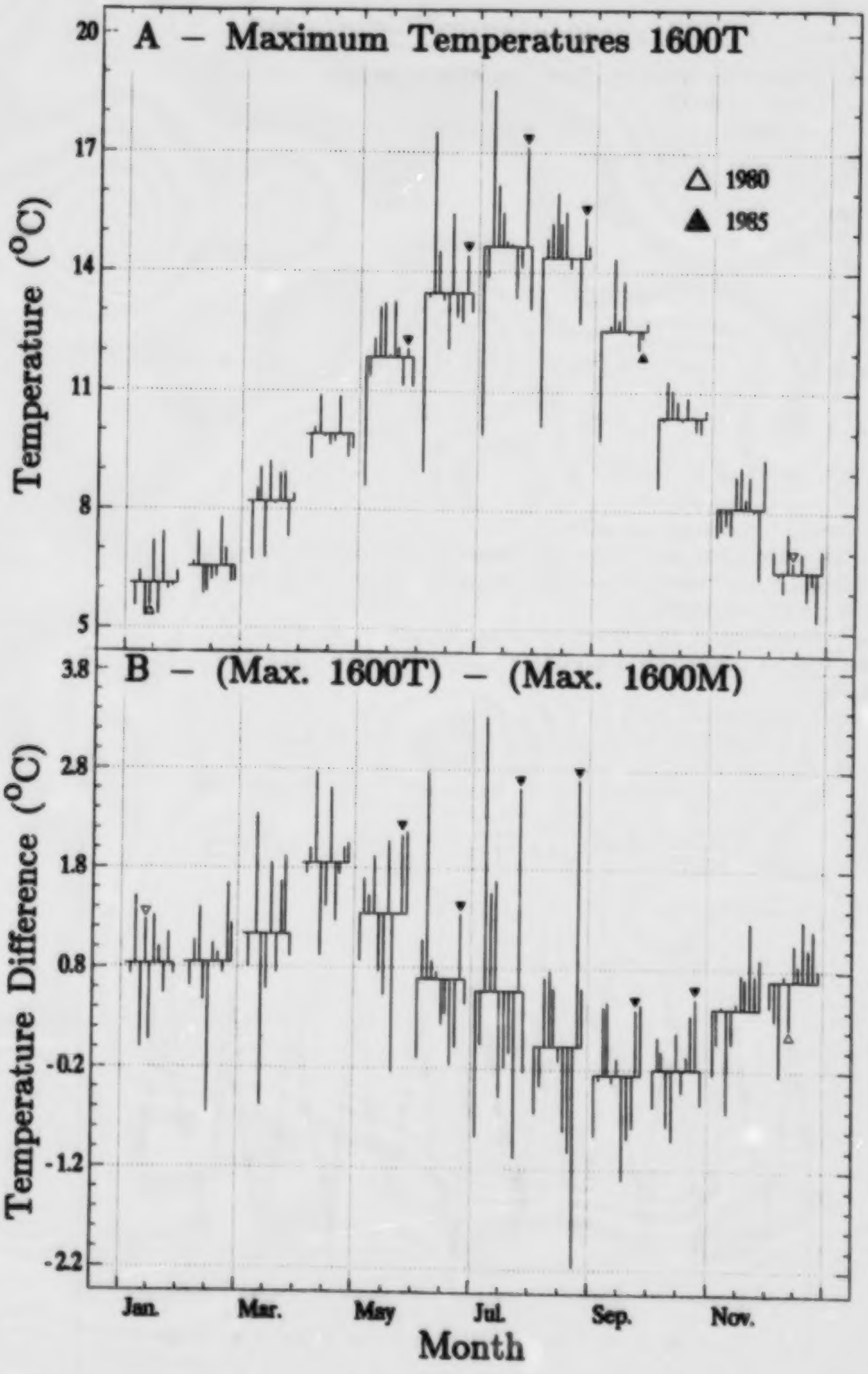


Figure 5. Seasonal subseries plots of A) mean monthly maximum temperatures in 1600T and B) difference in mean monthly maximum temperatures between 1600T and 1600M, both from May 1976 to December 1986.

Table 1. Regression model for herbicide effects on mean temperatures in 1600T

| Variable | Coefficient | S error | $p^e$ |
|---|---|---|---|
| Intercept | 2.710 | 0.144 | <0.001 |
| TMean 1600M[a] | 0.727 | 0.011 | <0.001 |
| Spring[b] | 0.422 | 0.076 | <0.001 |
| Summer.Hrb1[c] | 0.753 | 0.139 | <0.001 |
| Ireveg[d] | -0.952 | 0.226 | <0.001 |

$n = 265$ Adjusted $R^2 = 0.957$ $S_{est} = 0.518$

[a] Mean weekly temperature at 1600M.

[b] Dummy variable equal to 1.0 for all observations from Feb.-May and 0.0 elsewhere, and makes a seasonal adjustment in the relationship between 1600T and 1600M.

[c] Dummy variable equal to 1.0 for all observations in the first or second summers (June-Sept.) after herbicide application and 0.0 elsewhere.

[d] Index of revegetation explained in the text.

[e] Two-tailed probability for rejection of the hypothesis that the parameter estimate = 0.0.

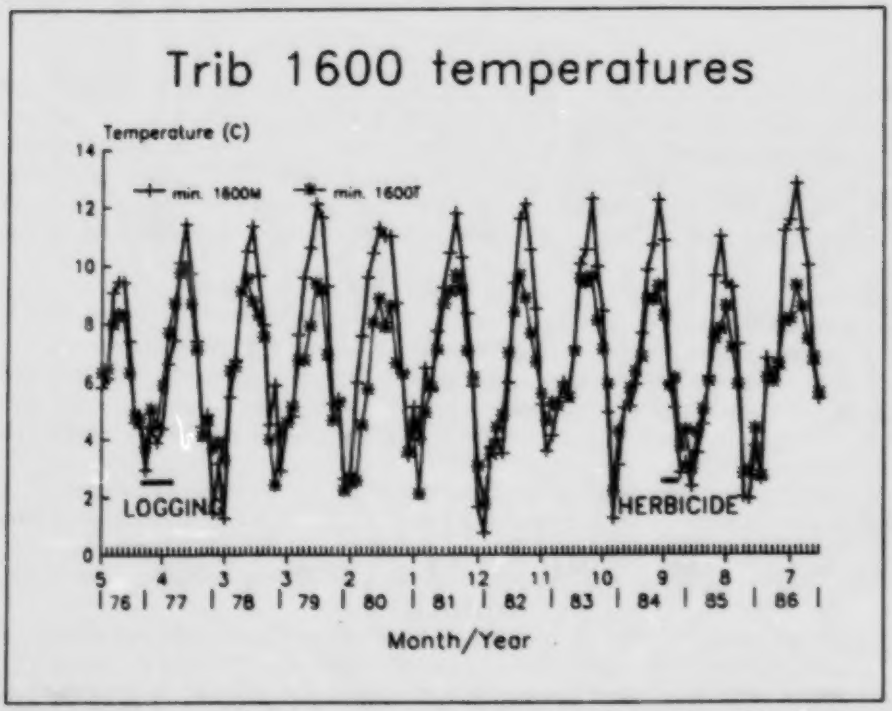


Figure 6. Mean minimum monthly temperatures in 1600M and 1600T from May 1976 to December 1986.

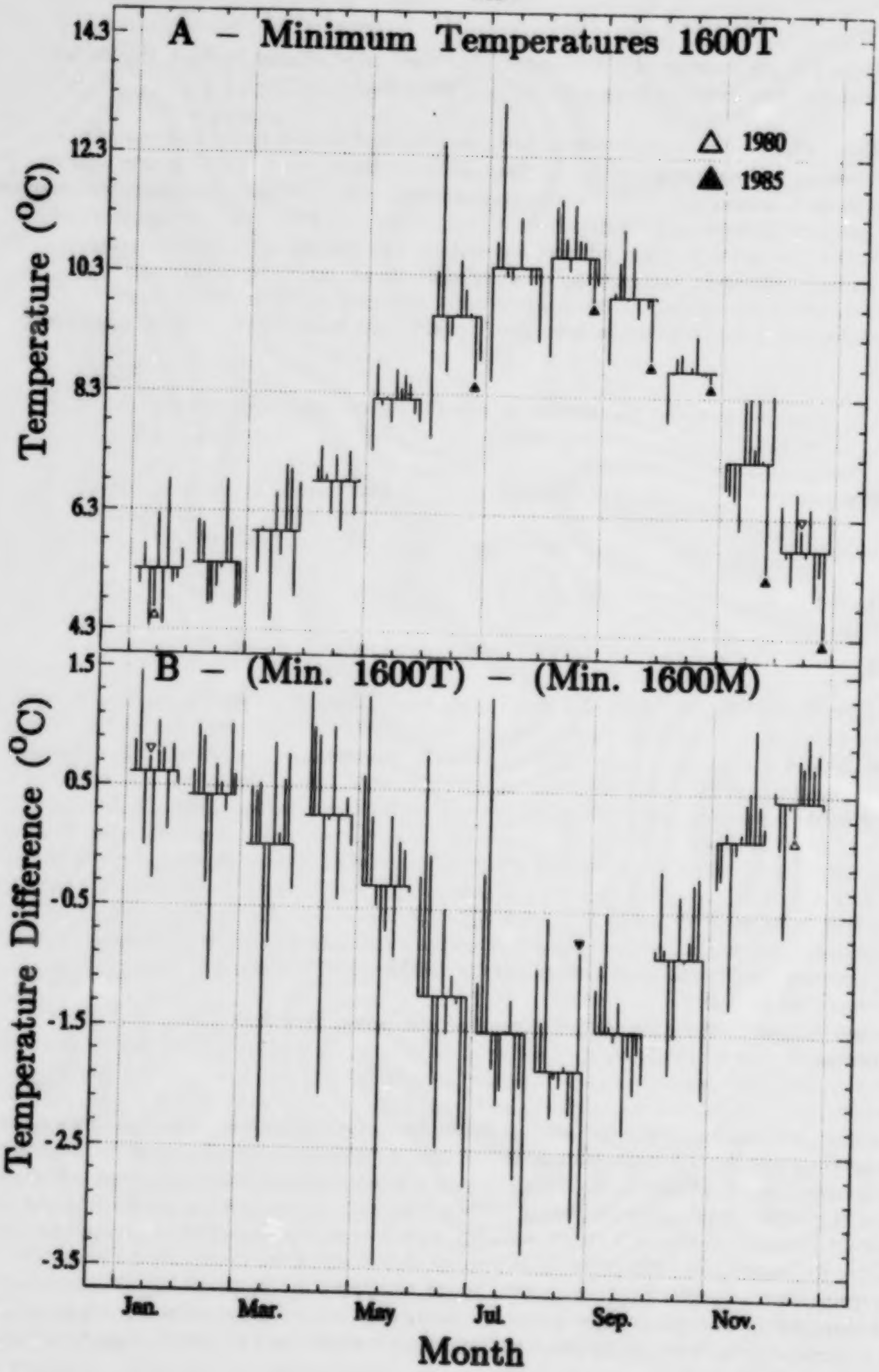


Figure 7. Seasonal subseries plots of A) mean monthly minimum temperatures in 1600T and B) difference in mean monthly minimum temperatures between 1600T and 1600M, both from May 1976-December 1986.

along the tributary in the summer of 1986 indicated that many trees affected by the herbicide had re-sprouted and that the canopy was again closing over the tributary.

Significant effects on maximum temperatures were detected in both spring and summer in both years following herbicide application. In 1985, summer maxima were 2.7°C greater and spring maxima were 0.68°C greater (Table 2). In the second spring after application maximum temperatures increased slightly but average summer effects decreased by half to 1.4°C. The near constancy of the herbicide effect in spring perhaps indicates that leaf-out was delayed in the second spring following treatment. However, there are no observational data available to confirm this. The non-significance of the re-vegetation index suggests that re-vegetation around 1600T was not significantly affecting the relationship between absolute maximum temperatures in 1600T and 1600M.

Table 2. Regression model for herbicide effects on maximum temperatures in 1600T.

| Variable | Coefficient | S error | p[c] |
|---|---|---|---|
| Intercept | 1.651 | 0.183 | <0.001 |
| TMax 1600M[a] | 0.879 | 0.016 | <0.001 |
| Spring | 1.173 | 0.148 | <0.001 |
| Summer.Hrb1[b] | 2.726 | 0.229 | <0.001 |
| Summer.Hrb2[b] | 1.375 | 0.228 | <0.001 |
| Spring.Hrb1[b] | 0.679 | 0.243 | 0.006 |
| Spring.Hrb2[b] | 0.755 | 0.260 | 0.004 |

$n = 265$ Adjusted $R^2 = 0.938$ $S_{est} = 0.872$

[a] The absolute weekly maximum temperature in 1600M.

[b] as described in Table 1.

[c] The two-tailed probability for rejection of the hypothesis that the parameter estimate = 0.0.

Minimum temperatures were also affected by the herbicide application (Table 3). Immediately after logging, minimum temperatures in 1600T during the summer (April-September) increased relative to temperatures in 1600M (Fig. 7B). Minimum temperatures generally increased at both sites as well (Fig. 7A). In the years following logging minimum temperatures in 1600T fell relative to those in 1600M probably as a result of regrowth of the canopy. That relative decline was slowed during the summer of 1985 probably as a result of removal of the canopy by the herbicide. Minimum temperatures at other times of the year appear unaffected by the herbicide. The inclusion of the "Summer.Hrb2" in the regression model, probably does not indicate a herbicide effect. Rather, it indicates a resumption of the decline of minimum temperatures in 1600T relative to those in 1600M.

Table 3. Regression model for herbicide effects on minimum temperatures in 1600T.

| Variable | Coefficient | S error | $p^c$ |
|---|---|---|---|
| Intercept | 2.565 | 0.160 | <0.001 |
| TMin 1600M[a] | 0.630 | 0.879 | <0.001 |
| Summer.Hrb2[b] | -0.809 | 0.184 | <0.001 |
| Ireveg[b] | -0.775 | 0.296 | 0.009 |

n = 265 Adjusted $R^2 = 0.904$ $S_{est} = 0.640$

[a] Absolute weekly minimum temperature in 1600M.
[b] as described in Table 1.
[c] Two-tailed probability for rejection of the hypothesis that the parameter estimme = 0.0.

## DISCUSSION

The physical basis of increased water temperature following removal of the forest canopy is well understood (Beschta et al. 1987). Water temperatures should increase after removal or defoliation of riparian vegetation because of increased penetration of sunlight to the stream. The increases in temperatures that were observed in 1600T the year after herbicide application were less than those observed after logging, and temperatures rapidly returned to pre-spray levels with the rapid recovery of the affected trees. Had the herbicide been more effective, temperatures in 1600T would have increased to levels comparable to those observed 2 yr after logging. Furthermore, recovery would have taken much longer and would not have been observed within the 2-yr study period. The temperature increases observed after herbicide application were generally consistent with those observed in other studies after physical or chemical removal of riparian vegetation (Corbett and Heilman 1975; Lynch et al. 1975; Rishel et al. 1982).

The biological significance of the observed and potential temperature increases following spraying should also be considered. Increases in summer mean and maximum temperatures following logging and spraying were not large enough to endanger resident juvenile salmonids, (except, perhaps for a few days each summer when maximum temperatures exceeded 22°C). However, Carnation Creek is a cooler stream (Holtby 1988a) than many other streams where herbicide application is likely. In warmer areas such as the east coast of Vancouver Island, temperature increases following logging are sufficient to stress fish and are of concern. Since temperature increases following spraying are comparable to those following logging, I would infer that herbicide-related increases in water temperatures would also be of concern.

Most of the effects of temperature change on the salmon of Carnation Creek, both beneficial and detrimental, are associated with small temperature changes in the late winter and spring (Holtby 1988b). Temperature changes comparable to those observed after logging were observed in 1600T the year after spraying. While 1600T is not a significant spawning area for coho salmon, it is an important over-wintering area for coho fingerlings. As much as 20% of the yearling smolt production has come from this tributary. With the accelerating degradation of the main stream channel and the possibility that smolt production is becoming more dependent on the tributaries (T.G. Brown, pers. comm. Pacific Biological Sta., Nanaimo), detrimental impacts on tributary production are of concern. Small increases in temperature in the early spring have been shown to be associated with earlier smolt migration which, in turn, is associated with decreases in smolt-to-adult survival of as much as 30% (Holtby 1988). Smolt exodus from 1600T is correlated with spring temperatures there (Holtby and Baillie 1989). However, spring temperatures were not significantly higher in 1600T in the spring of 1985, and it is unlikely that smolt movements were affected by the herbicide application. However, the use of a more effective herbicide would have removed more of the canopy for a longer period, possibly leading to larger temperature increases than were actually observed in 1600T.

## ACKNOWLEDGEMENTS

This study was made possible by an operating grant to the author from the Forest Resource Development Agreement, administered through the British Columbia Ministry of Forests and the Canadian Forestry Service. The study was part of the Carnation Creek Experimental Watershed Project, a multidisciplinary forestry-fishery study funded the Canadian Dept. of Fisheries and Ocean, the Canadian Forestry Service, Atmospheric Environment Service and Inland Waters Directorate of Environment Canada, the B. C. Ministry of Forests, the B. C. Ministry of Environment and MacMillan Bloedel Ltd. Thanks to the many individuals who have contributed to the collection of data used in this study.

## LITERATURE CITED

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. pp. 191-232. In E. F. Salo and T. W. Cundy (eds.) Streamside Management: Forestry and fishery interactions, College of Forest Resources, Contribution No. 57. Univ. of Washington, Seattle, WA 98195.

Corbett, E. S. and J. M. Heilman. 1975. Effects of management practices on water quality and quantity: The Newark, New Jersey, Municipal Watersheds. p. 47-57. In Proceedings of a Symposium on Municipal Watershed Management, USDA For. Serv. Gen. Tech. Rep. NE-13. Northeastern For. Exp. Stn., Broomall, PA.

Holtby, L. B. 1988a. The effects of logging on stream temperatures at Carnation Creek. pp. 118-122. In T. W. Chamberlin (ed.) Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biol. Sta., Nanaimo, B. C. V9R 5K6. 244 p.

Holtby, L. B. 1988b. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and resultant impacts on the coho salmon (*Oncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 45:502-515.

Holtby, L. B. and S. J. Baillie. 1989. Effects of the herbicide Roundup on the coho salmon fingerlings of an oversprayed tributary of Carnation Creek, British Columbia. This proceedings.

Lynch, J. A., W. E. Sopper, E. S. Corbett and D. W. Aurand. 1975. Effects of management practices on water quality and quantity: The Penn State Experimental Watersheds. pp. 32-46. In Proceedings of a Symposium on Municipal Watershed Management, USDA For. Serv. Gen. Tech. Rep. NE-13. Northeastern For. Exp. Stn., Broomall, PA.

Reynolds, P. E., J. C. Scrivener, L. B. Holtby and P. D. Kingsbury. 1989. Overview of Carnation Creek herbicide project: historical, perspective, experimental protocols and spray operations. This proceedings.

Rishel, G. B., J. A. Lynch and E. S. Corbett. 1982. Seasonal stream temperature changes following forest harvesting. J. Environ. Qual. 11:112-116.

Scrivener, J. C. 1988. Effects of logging on the chum salmon of Carnation Creek. p. 150-158. In T. W. Chamberlin (ed.) Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biol. Sta., Nanaimo, B. C. V9R 5K6. 239 p.

# EFFECTS OF THE HERBICIDE ROUNDUP[1] (GLYPHOSATE) ON PERIPHYTON IN CARNATION CREEK, BRITISH COLUMBIA

L. Blair Holtby & Steven J. Baillie
Biological Sciences Branch
Department of Fisheries and Oceans
Pacific Biological Station
Nanaimo, B.C. V9R 5K6

## ABSTRACT

Periphyton standing crops and accumulation rates were monitored at several sites in the main-stem and valley-bottom tributaries of Carnation Creek for 18 months after the herbicide ROUNDUP was applied at a rate of 2.2 kg glyphosate ha$^{-1}$ to much of the valley floor of the watershed. One tributary was over-sprayed. There is evidence of direct toxicity of some herbicide component two weeks after the mid-September application. In the year following spraying there was some localized enhancement of production as the periphyton responded to increased levels of phosphorus immediately downstream of the over-sprayed tributary.

## INTRODUCTION

The periphyton are the algae that are attached to the bottom substrate of streams. Energy inputs from the periphyton are a significant component of the energy budget of streams (Cummins 1974), and periphyton constitute an important food source for many of the insects and other invertebrates that are eaten by stream fishes (Lamberti and Resh 1983). Many factors are known to affect algal abundance and productivity in streams. In particular, changes in temperature (Phinney and McIntire 1965), light (Murphy et al. 1981), substrate composition (McConnell and Sigler 1959), and nutrient concentrations (Likens et al. 1970; Stockner and Shortreed 1978) have been experimentally demonstrated to affect stream periphyton. The application of herbicides in the riparian zone has the potential to affect stream temperatures, incident light intensities and nutrient levels and thereby affect stream periphyton. As part of the Carnation Creek herbicide experiment, we monitored periphyton biomass and accumulation rates in areas of the stream affected by the application of the herbicide ROUNDUP in the riparian zone of a valley-bottom tributary (Reynolds et al. 1989). In this paper we will describe the effects of the herbicide around the time of application and effects observed during the year after spraying.

## METHODS

We used 15 samplers, patterned after those used by Stockner and Shortreed (1976), to sample the periphyton. Plexiglass plates (30.5 x 50.8 x 0.64 cm) were divided into five equal strips by deeply inscribing lines on their upper surfaces. The upper surfaces of the plates were roughened using a fine grit sanding disk on an electric drill. The plates were attached with stainless steel bolts to concrete blocks weighing ~50 kg. The samplers were placed in the stream and tributaries by burying the concrete block in the substrate with the long axis of the plates perpendicular to the stream flow. Four of our sites were located in the main channel of Carnation Creek (Fig. 1). Two of the four sites (1610M and 2600M) were located above the confluence of 1600T and the main-channel and would not have been affected by the herbicide application. One site (1590M) was located immediately downstream of the confluence while the fourth site

---

[1] Registered trademark of Monsanto Corporation, St. Louis, MO.

(250M) was located 50 m downstream of B-weir, at least 300 m downstream of treated areas. The samplers were placed in protected areas of pools with low or moderate stream flows (Fig. 1). The samplers were placed in the stream on July 27, 1984, and cleaned on August 10, 1984. Regular monthly sampling was begun in September 1984. On September 5, 1984, 9 days before the herbicide application, samples were taken from only two of the five strips of eight of the samplers (identified on Fig. 1). The remaining three strips on each of the samplers were sampled on September 20, 6 days after spraying.

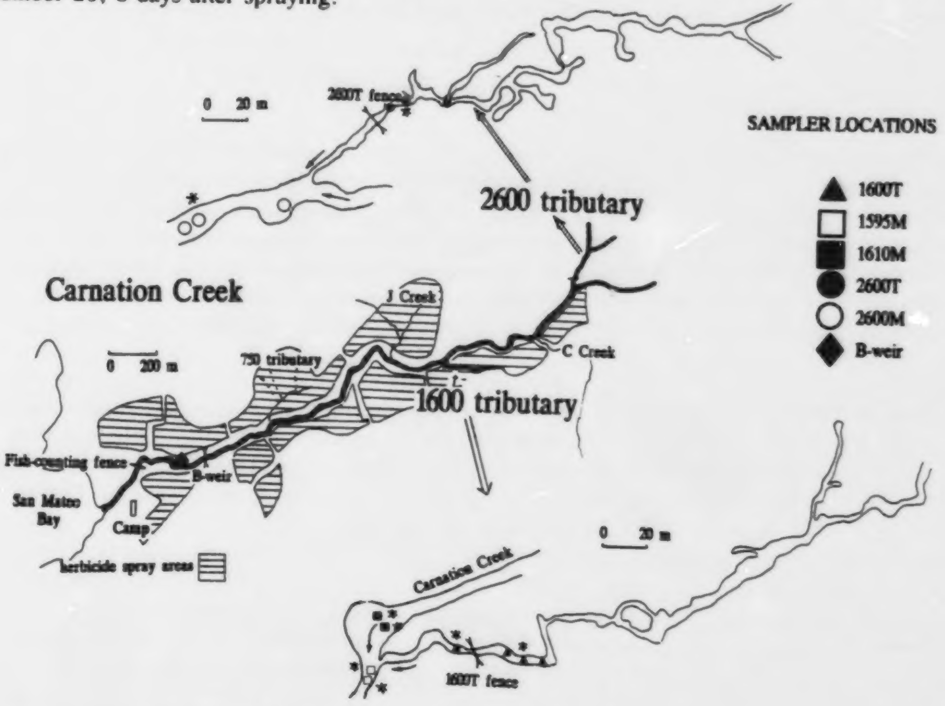

0 20 m
2600T fence
2600 tributary
SAMPLER LOCATIONS
▲ 1600T
□ 1595M
■ 1610M
● 2600T
○ 2600M
◆ B-weir
Carnation Creek
J Creek
0 200 m
750 tributary
C Creek
1600 tributary
Fish-counting fence
B-weir
San Mateo Bay
Camp
herbicide spray areas ▤
0 20 m
Carnation Creek
1600T fence

Figure 1. Schematic map of the study area showing location of samplers. Samplers marked by * were partially sampled before and after the herbicide application.

Sampling was done as follows: a plate was detached from its block and carefully removed from the water, macro-invertebrates (mostly chironomid larvae) were removed with fine forceps and the accumulated growth on each of the five strips was scraped into a separate glass jar with a razor blade while the surface was washed with filtered (0.45 $\mu$m pore size) stream water. The plate was then replaced on the sampler. If necessary, filtered water was added to the jars to bring their contents to ~50 mL. Within 2 h of sampling the contents of each jar were split three ways. For chlorophyll determination, 5-10 mL were withdrawn using a precision 5-mL pipette and filtered at low vacuum through 0.45 $\mu$m cellulose nitrate filters. A few drops of saturated $MgCO_3$ solution were added during filtration to prevent acidification prior to chlorophyll analysis. The filters were folded in half, wrapped in Al-foil, and stored with desiccant in sealed containers in a freezer. For determination of dry weight and ash-free, dry-weights, 5-10 mL were withdrawn from the sample jars and filtered at low vacuum through 0.45 $\mu$m cellulose filters that had been previously dried at 50°C and individually weighed. These filters were stored the same way those for the chlorophyll determinations were. The volume of the remaining sample was measured, the sample was placed in a 100 mL glass bottle and preserved with acidified Lugol's solution.

Chlorophyll was extracted using methods of Yentsch and Menzel (1963). The frozen filters were macerated in a tissue grinder with 10 mL of 90% acetone. During maceration the tissue grinder was held in an ice bath. Chlorophyll a content was determined with a periodically calibrated flourometer.

Dry weights were determined after re-drying the cellulose filters at 50°C for 12 h. Ash-free dry weights (AFDW) were determined after ashing the filters at 260°C for 4 h. Carbon was assumed to be 50% of the AFDW (Stockner and Armstrong 1971).

## RESULTS

Our measurements of chlorophyll a standing crops and net production (accumulation) rates were greater than any observed by Stockner and Shortreed (1978) during the pre-logging and immediate post-logging periods (Table 1). We do not know with certainty whether the increased abundance and activity of the periphyton that is suggested by our measurements are real or caused by methodological differences. Although in comparison with other systems, Carnation Creek during 1985 was certainly relatively unproductive (Table 1), it is not among the least productive aquatic ecosystems ever studied at temperate latitudes as implied by Stockner and Shortreed (1976).

Table 1. Comparison of average growing season chlorophyll a standing crops and net production rates of various periphyton communities. The table has been adapted from Stockner and Shortreed (1976). Nutrient concentrations are averages over the water year (Oct.-Sept.) expected at B-weir at flows of 105 L·ha·d$^{-1}$ (Scrivener, this proceedings)

| | | | Nutrients | |
|---|---|---|---|---|
| Community | Chlorophyll a (mg.m$^{-2}$) | net production (mgC.m$^{-2}$.day$^{-1}$) | P-PO4 (µg at·L$^{-1}$) | N-NO3 |
| Carnation Creek (1974-1975)<br>(Stockner and Shortreed 1976) | 1.6 | 20 | .05 | 2.5 |
| Carnation Creek (1978-1979)<br>(Shortreed and Stockner 1982) | 2.2 | 28 | .10 | 5.5 |
| Carnation Creek (1985)<br>(this study) | 12.4 | 70 | .08 | 1.8 |
| Alsea streams, Oregon<br>(Hansmann 1969) | 60 | 380-580 | .41 | 13.8 |

Our attempts to detect short-term effects of herbicide application were inconclusive. During the first half of September 1984, chlorophyll standing crops and accumulation rates increased at all sites (Table 2; Fig. 2). The mid-September measurement date was 6 days after the herbicide application and there was no indication of an adverse effect in the over-sprayed sites at that time. The increases in standing crops and accumulation rates continued in the second half of September but only at the sites upstream or far downstream of 1600T. Chlorophyll standing

Table 2. Chlorophyll a standing crops and AFDW accumulation rates during August and September 1984 and 1985. Standard deviations and sample sizes are indicated in brackets

| site | | 1984 | | 1985 | |
|---|---|---|---|---|---|
| | Aug. | | Sept. | Aug. | Sept. |
| | | | before - spray - after | | |
| | | | standing crop ($mg.m^{-2}$) | | |
| 250M | 1.09 | - | 6.12 | 10.8 | 9.36 |
| | ( 7,0.31) | | (10,2.40) | ( 5,2.15) | (5,3.01) |
| 1590M | 0.45 | 4.28 | 0.16 | 15.0 | 74.5 |
| | ( 7,0.29) | ( 3,0.38) | ( 5,0.13) | ( 5,7.91) | (5,42.9) |
| 1610M | 0.69 | 16.2 | 16.4 | 7.55 | 7.18 |
| | ( 7,0.14) | ( 3,4.18) | ( 5,5.49) | ( 5,1.43) | (5,5.34) |
| 1600T | 0.22 | 1.36 | 0.30 | 0.47 | 0.22 |
| | ( 7,0.14) | ( 3,0.40) | (10,0.069) | (10,0.51) | (10,0.14) |
| 2600M | 0.31 | 2.21 | 13.3 | 1.09 | 19.5 |
| | ( 7,0.17) | ( 3,0.86) | ( 5,5.40) | ( 5,0.24) | (5,4.94) |
| 2600T | 0.83 | 4.13 | 5.54 | 0.45 | 2.89 |
| | ( 7,0.31) | ( 3,4.03) | ( 5,1.72) | ( 5,0.12) | (5,0.11) |
| A F DW accumulation rate ($mg.m^{-2}.day^{-1}$) | | | | | |
| 250M | 0.044 | - | 0.153 | 0.386 | 0.312 |
| | ( 7,0.013) | | (10,0.060) | ( 5,0.094) | (5,0.100) |
| 1590M | 0.20 | 0.107 | 0.005 | 0.535 | 2.48 |
| | ( 7,0.013) | ( 3,0.010) | (10,0.004) | ( 5,0.282) | (5,1.43) |
| 1610M | 0.030 | 0.405 | 0.511 | 0.269 | 0.239 |
| | ( 7,0.006) | ( 3,0.104) | (10,0.172) | ( 5,0.051) | (5,0.178) |
| 1600T | 0.010 | 0.034 | 0.009 | 0.017 | 0.007 |
| | ( 7,0.005) | ( 3,0.010) | (10,0.002) | ( 5,0.018) | (5,0.005) |
| 2600M | 0.014 | 0.055 | 0.414 | 0.039 | 0.650 |
| | ( 7,0.007) | ( 3,0.021) | (10,0.169) | ( 5,0.009) | (5,0.165) |
| 2600T | 0.035 | 0.103 | 0.173 | 0.016 | 0.096 |
| | ( 7,0.017) | ( 3,0.101) | (10,0.054) | ( 5,0.004) | (5,0.004) |

crops and accumulation rates at 1590M and 1600T were severely curtailed (Fig. 2: Table 2).. During the same period the following year, chlorophyll standing crops increased from September to October at all sites except 1600T, where they again declined (Table 2). Because of that decline in 1600T during the fall of 1985, we cannot be certain that the large declines in chlorophyll at 1590M and 1600T during October 1984 were associated with the herbicide. While the possibility that some component or by-product of ROUNDUP killed or adversely affected the periphyton in the stream cannot be ruled out, that result would raise the question of why the effect was apparently larger in 1600M than in 1600T, where the concentrations of the herbicide components were higher.

Unfortunately, a series of storms in October and November moved, buried or destroyed many of the samplers in the main-stem and made those in the tributaries inaccessible. Monitoring of the periphyton was begun again in February 1985 and continued through the 1985 growing season.

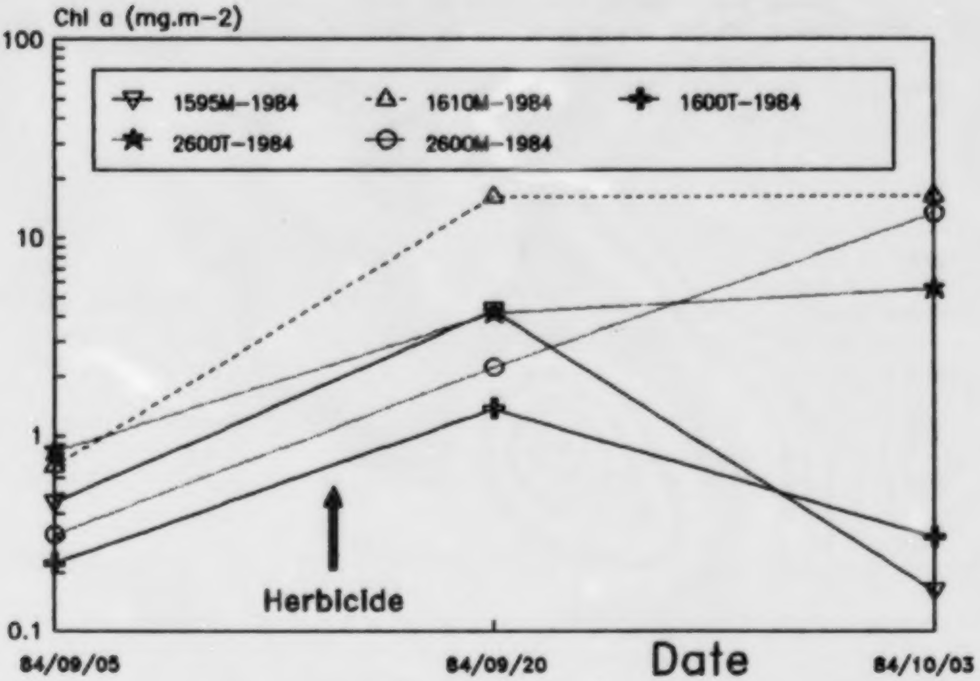


Figure 2. Chlorophyll a standing crops on the three sampling dates around the time of herbicide application.

The seasonal patterns of periphyton growth in 1985 varied between sites but in general, periphyton abundance was greatest during the warmest summer months and least during the winter (Figs. 3,4). In comparison to the seasonal patterns observed by Shortreed and Stockner (1982), periphyton abundance was much more dynamic, varying over at least an order of magnitude at all sites, in comparison to their observation of a 2 to 4-fold variation. Abundance during the winter remained at measurable levels at all sites. Periphyton abundance in the tributaries was an order of magnitude lower than in the main-stem (Fig. 3) and had a different seasonal abundance pattern, with highest abundance in the winter.

Scrivener (1989) has reported increased concentrations of P and N in 1600T and 1590M in the water in the year following spraying (October 1984-September 1985). The periphyton at 1590M appear to have responded to those nutrient increases. During September 1985 chlorophyll a standing crops at 1590M average 74.5 mg.m$^{-2}$, nearly 100-fold the observed levels during the same period in 1984. At the other main-stem sites, and notably at 1610M, periphyton abundances in September 1984 and 1985 were similar (Table 2).

The periphyton in 1600T showed no increase in abundance in 1985 compared to 1984. That result was unexpected. Temperatures in 1600T were warmer during 1985 because of the defoliation of much of the riparian alder (Holtby 1989), and, for the same reason, light levels must have been greater. Nutrient concentrations were also significantly greater (Scrivener 1989). Either the periphyton in 1600T were incapable of responding to these seemingly favorable conditions or additional growth was being grazed by the abundant invertebrate community of the tributary.

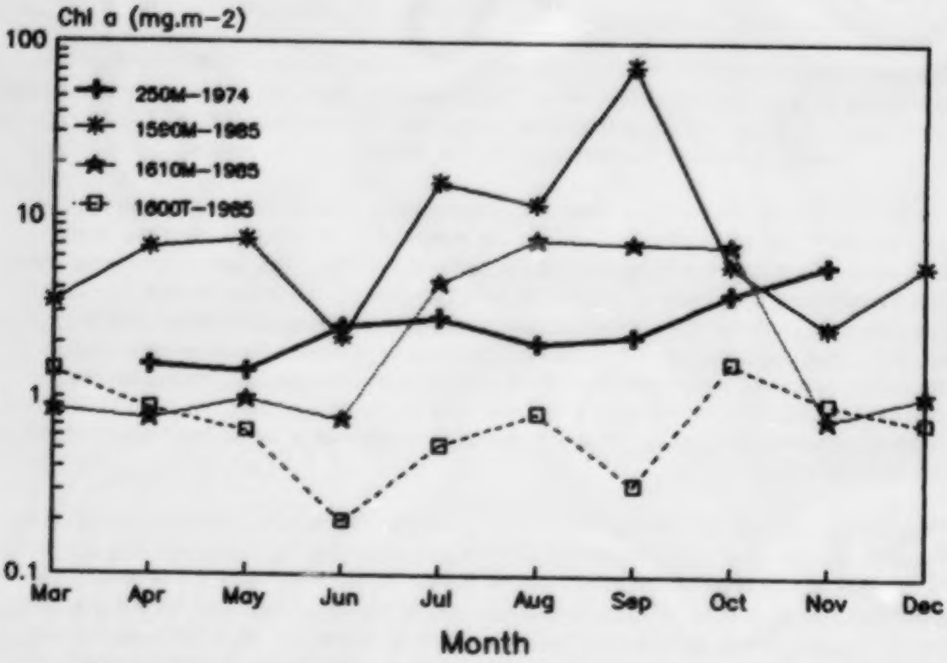


Figure 3. Seasonal patterns in chlorophyll a standing crops at 250M during 1974 and at the 1600 tributary sites in 1985.

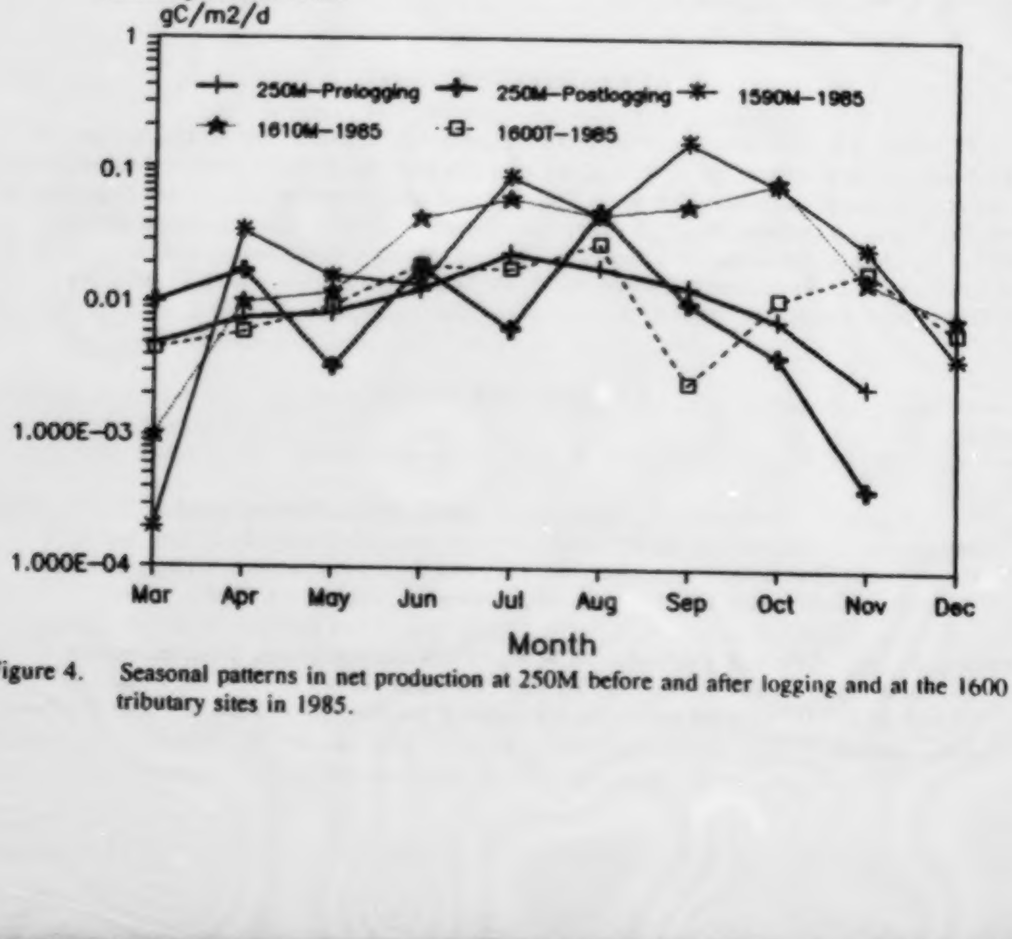


Figure 4. Seasonal patterns in net production at 250M before and after logging and at the 1600 tributary sites in 1985.

## DISCUSSION

We had hoped to use the periphyton data of Shortreed and Stockner (1982) for base-line levels of standing crop and accumulation rates. Unfortunately, either unforeseen differences in our methodologies or large changes in the periphyton community between 1980 and 1984 prevented us from doing so, effectively limiting the interpretation that we can give our results.

Declines in periphyton standing crops and accumulation rates at the two sites directly affected by the herbicide application, but only in the month after spraying, suggest that there were direct toxic effects of some component of the herbicidal spray. The little experimental data that do exist concerning the effects of glyphosate on algae indicate that under certain conditions of dose, temperature, and light, the chemical can inhibit photosynthesis (Grossbard 1985). However, in the only field study that I could find (Sullivan et al. 1981), no short-term toxic effects on stream and pond periphyton were detected in a coastal stream in Oregon after the application of ROUNDUP at similar levels to those used in this study. Sullivan et al. (1981) note that differences between sites and seasonality in periphyton abundance would have masked most short-term toxic effects.

Periphyton in Carnation Creek grow in an oligotrophic system, i.e. a system depauperate in nutrients. The element that is in particularly short supply is phosphorus (Stockner and Shortreed 1978), a situation that is apparently unusual on the Pacific coast, where nitrogen is usually the limiting nutrient (Gregory et al. 1987). It is not unreasonable to conclude that the periphyton responded to the increases in phosphorus that were observed in the year after spraying (Scrivener 1989). In keeping with the rapid uptake of phosphorus in nutrient limited systems (Lean 1973), the enhancing effect was probably confined to a short stretch of the main-stem immediately downstream of the confluence with 1600T.

## ACKNOWLEDEGMENTS

This study was made possible by an operating grant to LBH and a contract to SJB from the Forest Resource Development Agreement, administered through the British Columbia Ministry of Forests and the Canadian Forestry Service. The study was part of the Carnation Creek Experimental Watershed Project, a multidisciplinary forestry-fishery study funded the Canadian Dept. of Fisheries and Oceans, the Canadian Forestry Service, Atmospheric Environment Service and Inland Waters Directorate of Environment Canada, the B. C. Ministry of Forests, the B. C. Ministry of Environment and MacMillan Bloedel Ltd.

## LITERATURE CITED

Cummins, K. W. 1974. Stream ecosystem structure and function. BioScience 24:631-641.

Gregory, S. V., G. A. Lamberti, D. C. Erman, K V. Koski, M. L. Murphy and J. R. Sedell. 1987. Influence of forest practices on aquatic production. pp. 233-255. In E. F. Salo and T. W. Cundy (eds.) Streamside Management: Forestry and fishery interactions. College of Forest Resources, Contribution No. 57. Univ. of Washington, Seattle, WA 98195.

Grossbard, E. 1985. Effects of glyphosate on the microflora: with reference to the decomposition of treated vegetation and interaction with some plant pathogens. p. 159-185. In E. Grossbard and D. Atkinson (eds.) The Herbicide glyphosate. Butterworth & Co. (Publishers) Ltd., Toronto. 490 p.

Hansmann, E. W. 1969. The effects of logging on periphyton communities of coastal stream. Ph. D. Thesis. Oregon State Univ., Corvallis, OR. 120 p.

Holtby, L. B. 1989. Changes in the temperature regime of a tributary of Carnation Creek. British Columbia, over-sprayed with the herbicide ROUNDUP (glyphosate). This proceedings.

Lamberti, G. A. and V. H. Resh. 1983. Stream periphyton and herbivores: an experimental study of grazing by a caddisfly population. Ecol. 64:1124-1135.

Lean, D. R. S. 1973. Phosphorus dynamics in lake water. Science 179:678-680.

Likens, G. E., F. H. Bormann, N. M. Johnson, D. W. Fisher and R. S. Peirce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Monogr. 40:23-47.

McConnell, W. J. and W. F. Sigler. 1959. Chlorophyll and productivity in a mountain river. Limnol. Oceanogr. 4: 335-351.

Murphy, M. L., C. P. Hawkins and N. H. Anderson. 1981. Effects of canopy modification and accumulated sediment on stream communities. Trans. Am. Fish. Soc. 110:469-478.

Phinney, H. K. and C. D. McIntire. 1965. Effect of temperature on metabolism of periphyton communities developed in laboratory streams. Limnol. Oceanogr. 10:341-344.

Reynolds, P. E., J. C. Scrivener, L. B. Holtby and P. D. Kingsbury. 1989. Overview of Carnation Creek herbicide project: historical perspective, experimental protocols, spray operations. This proceedings.

Scrivener, J. C. 1989. Changes in concentration of dissolved ions following herbicide application (ROUNDUP) at Carnation Creek, British Columbia. This proceedings.

Shortreed, K. R. S. and J. G. Stockner. 1982. The impact of logging on periphyton biomass and species composition in Carnation Creek: a coastal rain-forest stream on Vancouver Island. British Columbia. p. 197-209. In G. F. Hartman (ed.) Proc. of the Carnation Creek Workshop: a ten-year review. Pacific Biol. Sta., Nanaimo, B. C. V9R 5K6. 404 p.

Stockner, J. G. and F. A. J. Armstrong. 1971. Periphyton of the experimental lakes area, northwestern Ontario. J. Fish. Res. Board Can. 28:215-229.

Stockner, J. G. and K. R. S. Shortreed. 1976. Autotrophic production in Carnation Creek, a coastal rainforest stream on Vancouver Island, British Columbia. J. Fish. Res. Board Can. 33: 1553-1563.

Stockner, J. G. and K. R. S. Shortreed. 1978. Enhancement of autotrophic production by nutrient addition in a coastal rainforest stream on Vancouver Island. J. Fish. Res. Board Can. 35: 28-34.

Sullivan, D. S. , T. P. Sullivan and T. Bisalputra. 1981. Effects of Roundup herbicide on diatom populations in the aquatic environment of a coastal forest. Bull. Env. Contamin. Toxic. 26:91-96.

Yentsch, C. S., and D. W. Menzel. 1963. A method for determination of phytoplankton chlorophyll and phaeophytin by fluorescence. Deep Sea Res. Oceanogr. Abstr. 10:221-231.

# LITTER-FALL AND DETRITAL DECOMPOSITION RATES IN A TRIBUTARY OF CARNATION CREEK, BRITISH COLUMBIA, OVER-SPRAYED WITH THE HERBICIDE ROUNDUP[1] (glyphosate)

L. Blair Holtby and Steven J. Baillie

Biological Sciences Branch
Department of Fisheries and Oceans
Pacific Biological Station
Nanaimo, B.C. V9R 5K6

## ABSTRACT

Litter-fall was measured in the riparian zone of a tributary over-sprayed with the herbicide ROUNDUP (glyphosate) for 18 months after application. Defoliation of the riparian zone of the tributary reduced deciduous litter-fall to approximately 6% of the expected total deposition of 300 $g.m^2.yr^{-1}$. Coniferous litter was a minor component at all treatment and control sites, averaging less than 1% of the total. At the three control sites coniferous litter-fall increased by an average of 296% in the year after spraying compared to the year before, but in the treatment area the increase was only 36%. Litter decomposition rates in water were variable in the three summers during which measurements were made. Decomposition rates were greatest in the over-sprayed tributary and lowest in the control tributary. Between-site differences in decomposition rates were probably the result of differences in their macro-invertebrate communities. Most of the between-year variability in decomposition rates was accounted for by differences in stream temperatures. The herbicide had no measurable effects on macro-invertebrate abundance or community composition for 22 months after application. Decomposition rates in the over-sprayed tributary increased in the summers after spraying, partly as a result of increased summer temperatures that resulted from defoliation of the riparian zone.

## INTRODUCTION

Allochthonous input of organic material, in the form of litter-fall, is the dominant energy source of small woodland streams (Hynes 1963; Fisher and Likens 1972). Well-developed conceptual models of the decomposition of litter in streams (Cummins 1974; Boling et al. 1975) indicate the length of time that large pieces of litter, and especially leaves, are retained in the stream is important in determining the extent to which organic matter is processed by the benthic community of micro-organisms and invertebrates. Retention is necessary to allow bacteria and fungi to colonize the litter and begin to metabolize it (Kaushik and Hynes 1971), a process termed conditioning (Cummins 1974). Although litter from different sources can be processed at very different rates, complete processing requires several months for deciduous litter and several years for coniferous litter (Culp and Davies 1982). Sites within the stream that trap litter for the several months required for processing should be important to the energy budget of the stream and to the production of fish.

---

[1] Registered trademark of Monsanto Corporation, St. Louis, MO.

In this study, a herbicide was used to defoliate the riparian alder surrounding a small, valley-bottom tributary of Carnation Creek (Reynolds et al. 1989). Such tributaries are important sites of detrital processing in hydrologically volatile systems in the Pacific Northwest. We have looked at the change in litter-fall following the herbicide application and associated changes in the processing of alder leaves and in the invertebrate community, both in the affected tributary and at unaffected sites elsewhere in the watershed, for two years following application.

## METHODS

Leaf-litter was collected at 35 sites (Fig. 1) along the stream channels of the treated tributary (1600T), the control tributary (2600T), and the main-stem of Carnation Creek near the confluences with the two tributaries (1600M and 2600M respectively). Litter was collected in trays made of wood frames, 9 cm deep and 0.16 $m^2$ in area, with bottoms made of heavy plastic sheeting. A couple of small holes were punched in the bottom to allow water to drain away. The trays were placed at ground level as close to the stream channels as possible. At each site, trays were placed near the trees in proportion to the canopy closure at the site, as estimated by eye. For instance, if canopy closure was estimated to be 50% then half of the trays were placed close to trees and the remainder in the open. Litter was collected periodically from each individual tray, bagged, and returned to the lab. There, deciduous and coniferous litter were sorted and the two fractions were dried for 24 h at approximately 70°C, cooled in a dessicator and weighed.

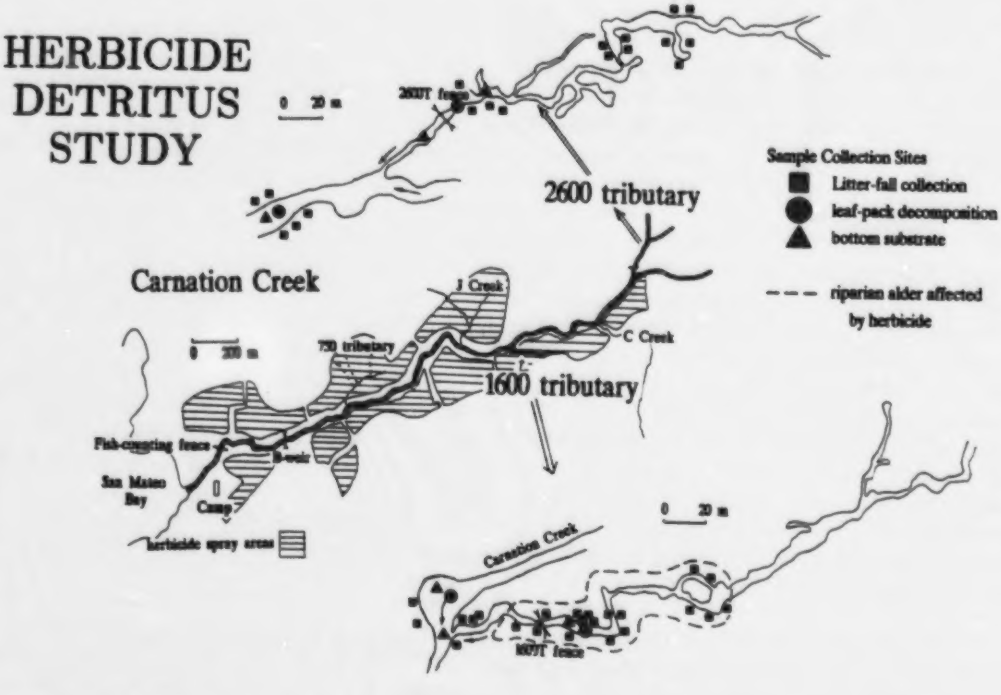

HERBICIDE
DETRITUS
STUDY
0 20 m
2600T fence
2600 tributary
Sample Collection Sites
■ Litter-fall collection
● leaf-pack decomposition
▲ bottom substrate
--- riparian alder affected by herbicide
Carnation Creek
J Creek
0 200 m
750 tributary
C Creek
1600 tributary
Fish-counting fence
B-weir
San Mateo Bay
Camp
herbicide spray areas
0 20 m
Carnation Creek
1600T fence

Figure 1. Sketch map of the two tributaries and surrounding main-stem areas showing sites of litter-collection, litter decomposition, and bottom substrate sampling. Approximate limits of dense alder overstory in 1600T are shown. Maps are not to scale.

The amounts and size distributions of litter and organic material in the bottom substrate were estimated. Samples were collected by forcing metal cylinders, 10 cm in diameter, into the bottom, capping the upper end with a tight plastic cap, carefully withdrawing the cylinder and sealing the bottom with another cap as it was withdrawn from the substrate. In the lab the substrate samples were washed through a graded series of sieves with nominal mesh sizes of 8, 4, 2, 1, 0.5, 0.25, 0.106, and 0.053 mm. After sieving, invertebrates were picked from each subfraction and preserved in formaldehyde for later enumeration and identification. Material retained on each sieve was oven dried at approximately 70°C for 24-48 hours, cooled and weighed to the nearest 0.05 g. Samples were taken in the summers of 1984-1986 from the heads of pools in the main-stem at 1600M and 2600M and in two tributaries, 1600T and 2600T (Fig. 1).

Litter decomposition rates were estimated by observing the rate at which alder leaves disappeared from small mesh bags placed in the stream. Leaf-pack studies have been extensively used by stream ecologists to study litter decomposition in streams. Immediately before starting an experimental series, fresh leaves were collected from the lower branches of alder trees around the Carnation Creek camp. After the herbicide application, leaves were collected from areas known not to have been over-sprayed. The leaves were dried for 24 h at 70°C, cooled in a dessicator and weighed to within 5 mg. Known weights of leaves (approx. 5-7 g) were then carefully placed in 15x20 cm packs made of plastic screening (mesh size approx. 3 mm). The packs were identified with numbered plastic disks enclosed with the leaves. The packs were then carefully carried to the four sites (Fig. 1), placed underwater in protected areas of pools, and tied to a strong line that extended across the channel. The packs were held on the bottom of the channel by placing rocks or debris on their attachment cords. Experimental series were run for 2-3 months in the summers of 1984-1986 and for 2-6 months in the winters of 1984/85 and 1985/86.

Periodically, individual packs were removed by carefully cutting the attachment string and sliding the pack into a 1 L container that had been filled with water at the site. The can was sealed with a tight fitting plastic lid and transported to the lab. At the time of collection, temperature and dissolved $O_2$ measurements were made with a YSI Model 57 oxygen meter at each site. The meter was calibrated in saturated water of known temperature using tables supplied with the instrument. In the lab, oxygen and temperature measurements were periodically made over a 4-8 h period following collection of the packs. Measurements of dissolved oxygen were made by first carefully inverting each can to mix the water and then replacing the plastic lid of a can with a lid through which the oxygen probe protruded. Although there was undoubtedly some gas exchange during the measurements, comparisons between samples should be valid. Measurements made on water samples without packs showed little change in dissolved $O_2$ levels after 8 h, even when initial $O_2$ values were well below saturation. Oxygen measurements were made only during the series that included the herbicide application and the following winter. After the 4-8 h period, the packs were opened and their contents placed in shallow, white trays. All of the leaves and leaf fragments were removed, gently washed, dried for 24 h at 70°C, cooled in a dessicator and weighed to within 5 mg. The contents of the pans, which included all of the invertebrates, were then screened through a 0.1 mm screen, and preserved in formaldehyde. Leaf-pack decomposition rates were estimated by fitting negative exponential curves to the proportion of dry leaf weight remaining over time (Peterson and Cummins 1974).

Invertebrates from the leaf packs and substrate samples were subsequently identified and enumerated. Most insects and other large organisms were identified to genus. Dipteran midges, copepods, worms, mollusks and water mites were identified as far as was practical for non-specialists, usually to family. Variation in the numbers of dominant taxa, those present in at least 30% of all samples, was summarized using principal components analysis (PCA). This technique enables the variation in community composition over time to be succinctly displayed on a graph. We used the PCA analysis to determine whether the herbicide application was associated with changes in community composition at the affected sites, both immediately after spraying and one and two years later. The role of macro-invertebrates in litter decomposition was assessed by comparing the number of animals in individual taxa and in the shredder functional group (Cummins 1974) with the rate of leaf-pack decomposition.

The sizes and densities of coho fingerlings in Carnation Creek during September from 1981-1986 were obtained from Andersen (1984,1985,1987). A fish fork-length - density relationship (log-log) was used to estimate fingerling densities at 28 sites within Carnation Creek during September 1983 from fork-length data (Andersen 1985). The variation in fish densities in the stream in relation to the outlet of the two major tributaries (1600T and 2600T) is used in the speculative discussion of the role of valley-bottom tributaries in the energy budget of the Carnation Creek ecosystem.

## RESULTS

Before the herbicide application, annual deciduous litter-fall ranged from 90 g.m$^2$ in the relatively open areas at 2600M to 350 g.m$^2$ under the dense alder canopy in the lower sections of 1600T (Fig. 2A). Coniferous litter-fall was one to two orders of magnitude less (Fig. 2B). These values are similar to those obtained by Neaves (1978) for similarly vegetated areas prior to logging.

The seasonal pattern of litter-fall indicates peak deposition in September-October, with the fall senescence and fall of deciduous leaves, virtually no litter-fall during the winter, and gradually increasing rates of deposition during the summer (Fig. 3). The yearly pattern of litter-fall at Carnation Creek is no different from those observed in other sites dominated by deciduous trees in the northern hemisphere (Dixon 1976), but is quite different from the patterns observed by Culp and Davies (1982) at the same sites several years earlier.

The herbicide had a pronounced effect on litter-fall at 1600T beginning in the early summer of 1985, the year after application (Fig. 2A,3). Deciduous litter-fall in the year after application fell to 30 g.m $^2$, less than 10% of the previous year. Total litter-fall at the other sites was similar in 1984 and 1985. The litter that did fall in 1985 at 1600T was largely from herbaceous plants growing near the ground that toppled, rather than fell, into the litter traps. Coniferous litter-fall at 1600T was similar in 1984 and 1985 (Fig. 2B). At two of the other three sites coniferous litter-fall increased substantially in 1985 (Fig. 2B). The reason for that increase is uncertain. There was no obvious increase in the height or number of conifers at any site and trap placement was not different in 1985 compared to 1984.

The size distribution of organic particles found in the substrate of 1600T appears to have changed in response to defoliation of the riparian alder (Fig. 4A). In the particle size spectra of Figure 4, leaves and leaf fragments predominate the size categories from 0.4-2 mm. Larger particles and especially those retained by the 8-mm sieve were woody debris, which is very resistant to fragmentation and decay. In the two summers following herbicide application there was a progressive decrease in the total weight of particles between 0.4 and 2 mm, probably a result of decreasing leaf deposition into 1600T. There was little change in the the number of particles above 4 mm and no consistent change in smaller particles. Organic matter in the substrate of the main channel at 1600M was considerably less abundant than in the tributary (Fig. 4B), and there was a notable absence of particles > 2 mm. The reasons why small particles were comparatively rare in 1985 compared to 1984 and 1986 are uncertain. The bottom samples from those years had comparatively large amounts of sand, and it is possible that the between-year differences are due to changes in the particle size composition of the gravels.

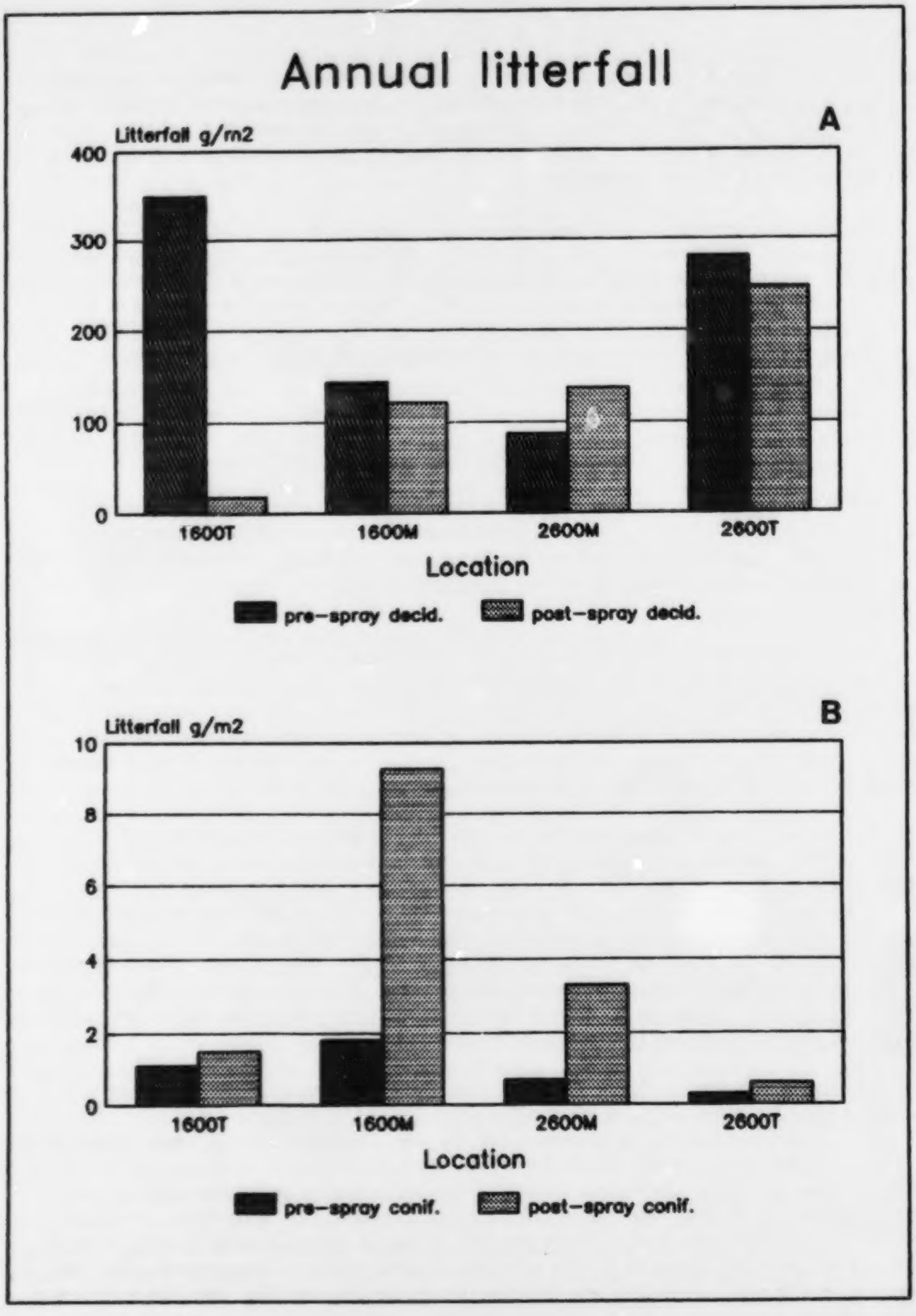


Figure 2. A) Deciduous and B) coniferous litter-fall at the main-stem and tributary sites from Aug. 1984 - Feb. 1986.

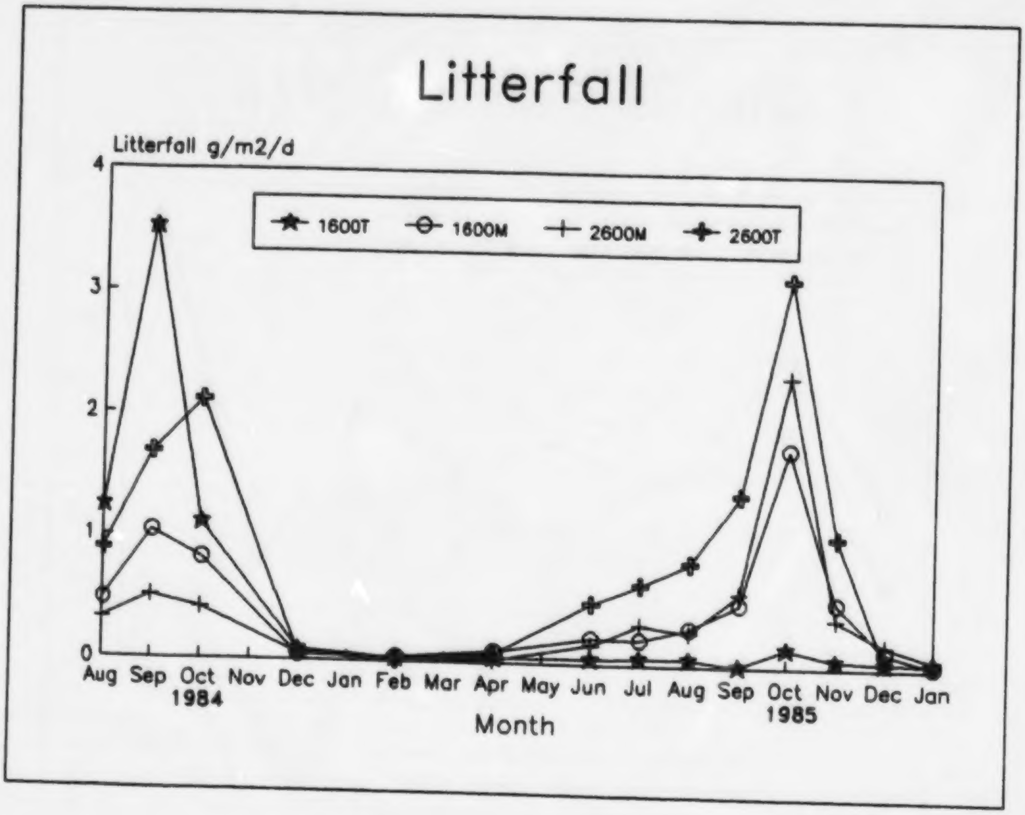


Figure 3. Comparison of total yearly litter-fall in 1984 and 1985 at the two tributary sites.

Differences in the decomposition rates between sites were probably related to differences in the invertebrate communities of the four sites. Decomposition rates (Table 1) and the patterns of decomposition (Fig. 5) in the two main-stem sites were very similar. At both of the main-stem sites decomposition appears to proceed in two stages which are related to the colonization of the leaf-packs by invertebrates in the shredder functional group (Fig. 6). Large-bodied shredders, in particular the gammarid amphipod *Anisogammarus*, were abundant in 1600T and the highest decomposition rates were observed there (Table 1). The timing of decomposition curves in this tributary is described very well by a negative exponential function (Fig. 5C). Decomposition rates in 2600T were slightly lower than those in the main-stem sites (Table 1), but the time patterns of decomposition (Fig. 5D) and the abundances of shredders (Fig. 6D) were similar to the main-stem sites.

The between-season and between-year differences in decomposition rate are largely attributable to temperature (Fig. 7). The relationship between decomposition rate and temperature is the same for the two main-stem sites and for 2600T, but a different relationship applies to 1600T (Fig. 7) where the rate of increase in the decomposition rate with temperature was greater than at the other sites.

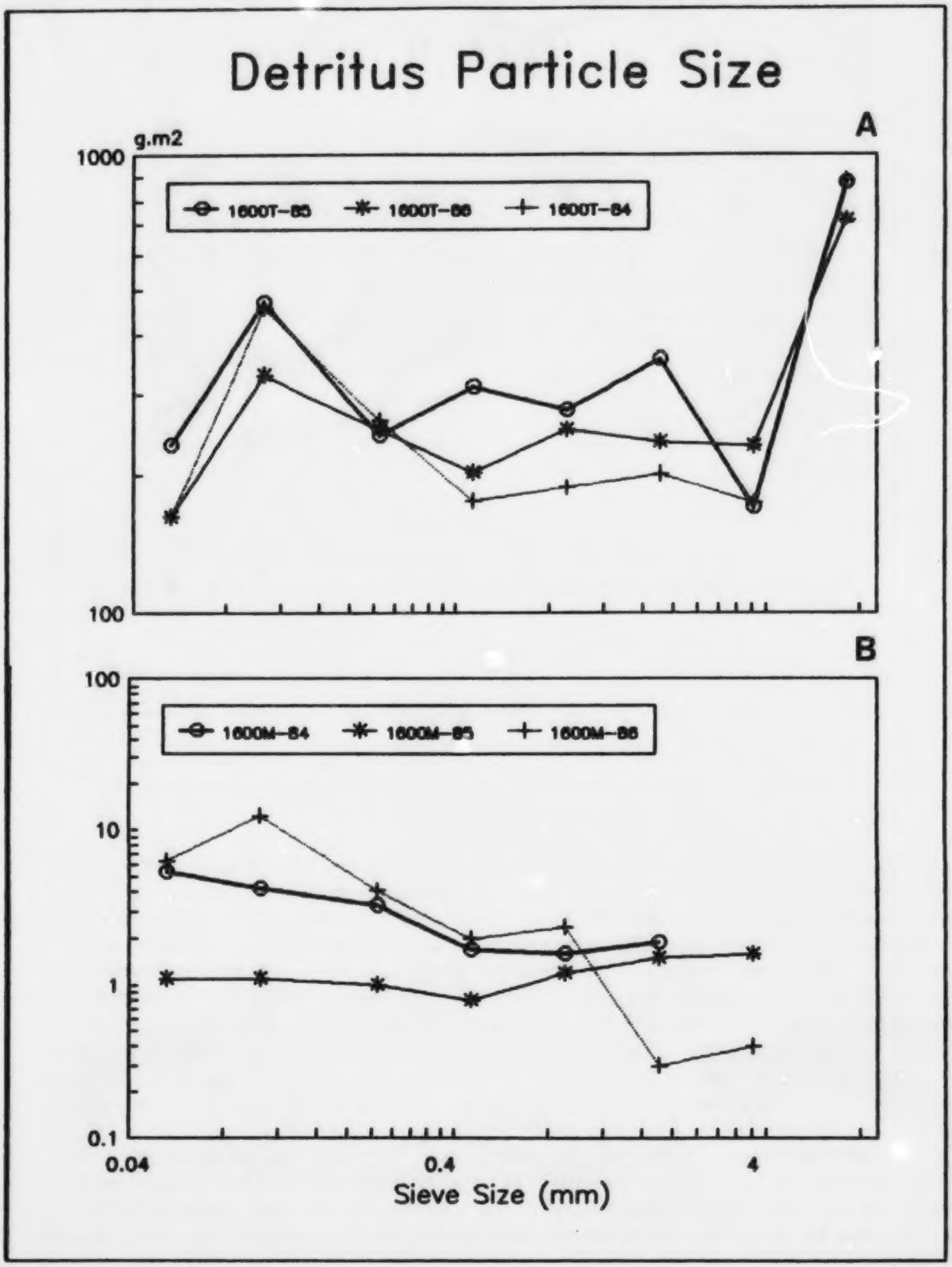


Figure 4. Size distributions of organic particles in the substrates of A) 1600T and B) 1600M during the summers of 1984-1986.

Table 1. Exponential rates of decomposition for leaf packs at four sites in Carnation Creek and tributaries. Mean temperatures during the experimental series are shown in brackets. Fall/winter measurements during 1984 could not be obtained from the main-stem sites due to high water levels

|  | Decomposition Rate |  |  |  |  |
|---|---|---|---|---|---|
| Site | summer 1984 | fall/winter 1984 | summer 1985 | fall/winter 1985 | summer 1986 |
| 1600T | -0.0477 | -0.0138 | -0.0498 | -0.0207 | -0.125 |
|  | (10.6) | (6.1) | (11.3) | (7.0) | (11.5) |
| 2600T | -0.0136 | -0.0071 | -0.0179 | -0.0051 | -0.0223 |
|  | (12.0) | (4.9) | (13.0) | (6.2) | (14.2) |
| 1600M | -0.0212 | n/a | -0.0369 | -0.02044 | -0.0244 |
|  | (11.9) | (5.0) | (11.3) | (6.5) | (13.3) |
| 2600M | -0.0217 | n/a | -0.0229 | -0.0185 | -0.0278 |
|  | (11.7) | (4.9) | (11.5) | (6.2) | (13.5) |

An indirect effect of the herbicide application is perhaps revealed by the anomalous decomposition rate observed in 1600T during the summer of 1986 (Fig. 7). The temperatures in 1600T were lower than they had been in 1985 (Holtby 1989) and the numbers of shredders and other invertebrates were similar to numbers in 1984 and 1985. In a study of the impacts of logging on litter decomposition, Webster and Waide (1982) observed a similar increase in decomposition rates that could not be accounted for by higher temperatures. They noted that their leaf-packs had become islands of high-quality food that were rapidly colonized and processed. The observed declines in both litter-fall (Fig. 3) and the amount of coarse particulate detritus (Fig. 4) in 1600T probably resulted in a similar "oasis-desert" situation existing in 1600T during the summer of 1986.

Oxygen consumption rates of the leaf-packs and the associated organisms were similar at all sites (Fig. 8). Consumption rates rose rapidly after introduction of the leaf-packs and had reached maximum values after 2-3 wk. Thereafter consumption rates declined exponentially. The rate of decline was inversely related to the decomposition rate. There was no change in oxygen consumption immediately after the application of the herbicide in 1600T (Fig. 8). If the herbicide had an effect on the respiration of the leaf-pack community then that effect was not measurable the day after application.

The principal component analysis indicated that there were three macro-invertebrate communities, which could be distinguished by the relative abundances of the 20 common taxa found in the leaf packs. The communities found at both main-stem sites were similar to each other, but different from the communities found in the tributaries. The two main-stem sites were characterized by an absence of the sand-flea *Anisogammarus*, the isopod *Asellus*, a snail (Planorbidae),

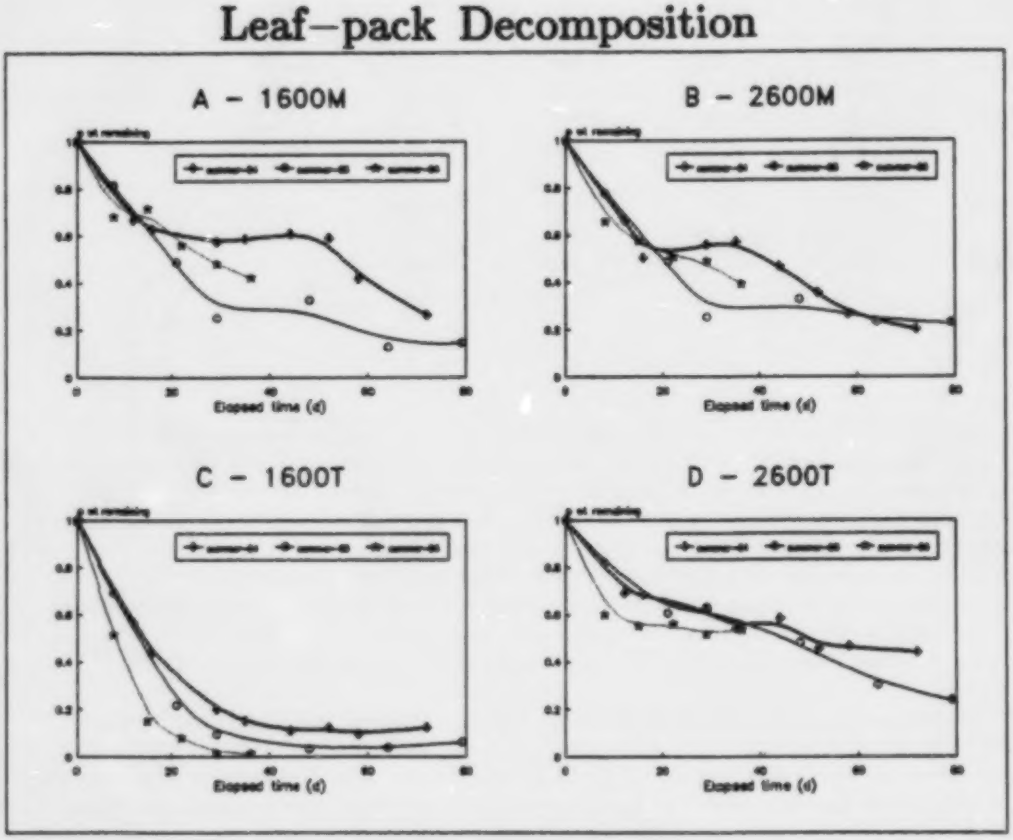
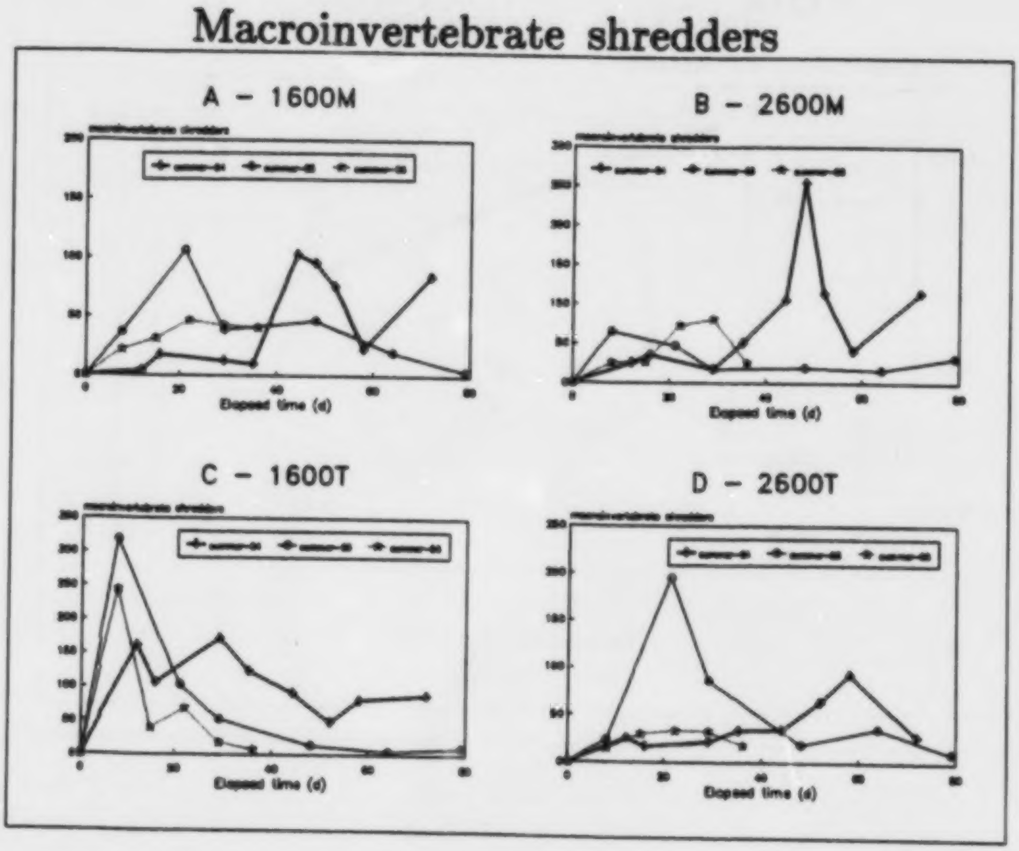


Figure 5. Proportion of dry weight remaining in the leaf packs at the four sites during the summers of 1984-1986, as functions of immersion time.



Macroinvertebrate shredders

Figure 6. Numbers of invertebrates in the shredder functional groups collected from the leaf packs at the four sites during the summers of 1984-1986 as functions of immersion time.

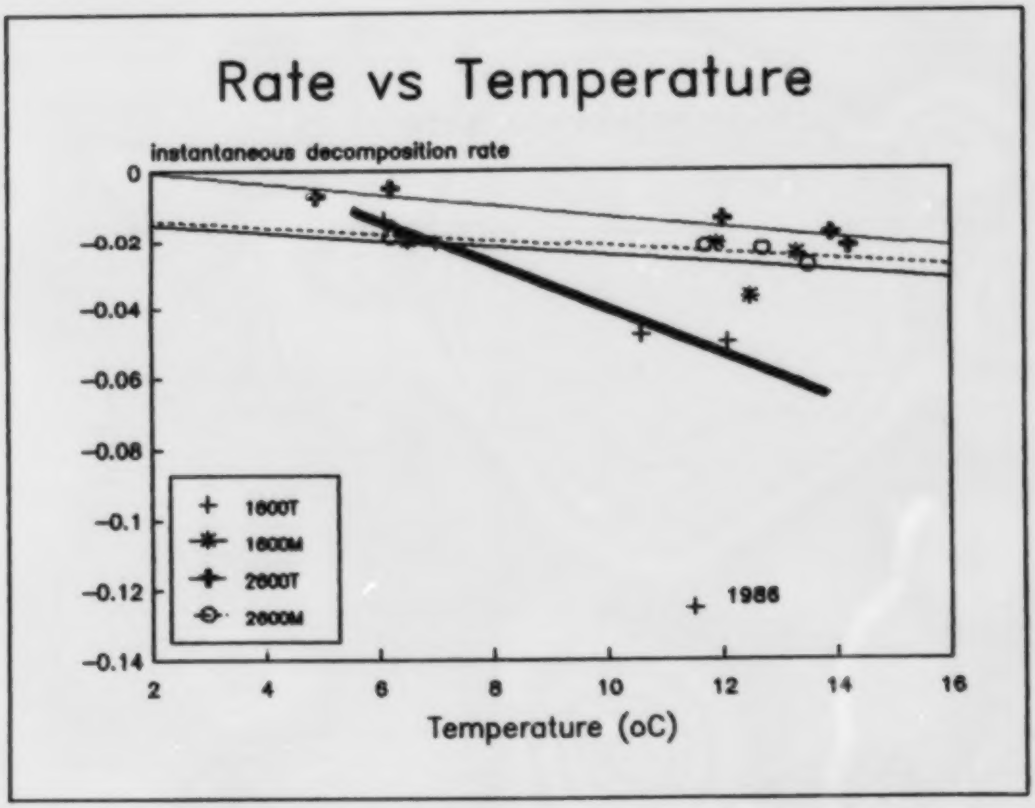


Figure 7. Instantaneous decomposition rates in the leaf packs from 1984-1986 as functions of mean temperature during immersion.

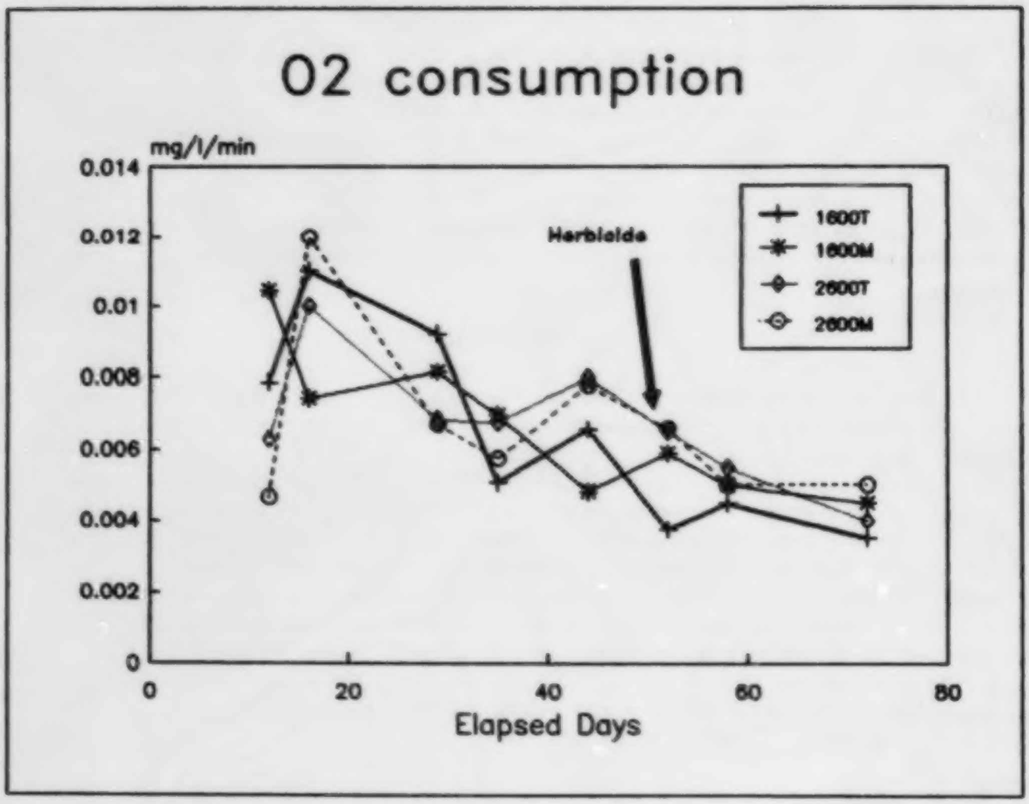


Figure 8. Oxygen consumption rates of leaf packs during the summer of 1984 as functions of immersion time of the leaf packs. The date of herbicide application at 1600T is indicated.

and a caddis fly of the family Polycentropodidae, and by the relative scarcity of the mayfly *Paraleptophlebia*, all of which were abundant in the tributaries. Taxa abundant in the main-stem but absent or rare in the tributaries included the mayfly *Baetis*, a caddis fly of the family Lepidostomtidae and the stonefly, *Capnia* (Table 2). The two tributary sites were distinguished by the relative abundances of *Anisogammarus* and *Asellus*, which were abundant in 1600T and ostracods, oligochaets, and gastropods, which were abundant in 2600T. Some taxa such as chironomid midges and cyclopoid and harpactacoid copepods were abundant at all sites. In functional terms, the communities of the main-stem were dominated by animals that collect suspended particles or scrape particles off solid substrates. The community of 1600T was dominated by shredders, animals that fragment and ingest large particles. The community of 2600T included several taxa that feed in rich organic oozes.

The PCA scores summarize patterns of variation in community composition and when PCA scores from the same sites are arrayed over time, time-dependent changes in community composition should be revealed. The time tracks of the leaf-pack communities (Fig. 9) show gradual development of the communities characteristic of the four sites, but there is no indication of large changes in community composition or changes in the abundance of dominant taxa around the time of spraying (Fig. 9). Although macro-invertebrate abundances were lower at all sites in 1985 and 1986 (Fig. 6), projection of the taxa abundances in those years into the component space defined by abundances in 1984, indicated that no change in community composition had occurred (Fig. 9).

## DISCUSSION

The application of herbicide to the riparian vegetation surrounding a small, valley-bottom tributary of Carnation Creek greatly reduced the amount of litter that fell into the tributary in the following year. As a result of the decrease in leaf litter input, the number of detrital particles 0.5-2 mm in size decreased in the two summers following herbicide application. Detrital processing rates were dependent on water temperatures and on site-specific assemblages of macroinvertebrates. Detrital processing rates were consistently higher at the site where the macroinvertebrate community was dominated by large-bodied taxa in the shredder functional group (Cummins and Klug 1979). In general, between-year differences in processing rates could be accounted for by variations in temperatures. In the summer of 1986, two years after the herbicide application, detrital processing rates in the over-sprayed tributary were much greater than expected, even after correcting for temperature. Such a result might be expected in a system where high quality food particles have become scarce and the experimenter artificially introduces packets of high quality food (Webster and Waide 1982).

Current conceptual models of stream ecosystems (Boling et al. 1975; Vannote et al. 1980) clearly indicate the importance of detrital inputs as the major energy source of small woodland streams. The utilization of detrital inputs is critically dependent on mechanisms that enhance the capture and retention of litter (Cummins et al. 1980; Petersen and Cummins 1974; Reice 1980). In coastal streams in the Pacific northwest, the highest stream flows, and presumably the fastest flushing of small debris, occurs in October-December, immediately after leaf-fall. Any structural characteristics of streams in this region that promote the retention of debris should be important modifiers of stream energy budgets. Small, valley-bottom tributaries typified by 1600T at Carnation Creek, because of their small size and low discharges, the large amount of woody debris they contain and their relatively high sinuosity, promote the retention of small debris such as leaves. The dense growth of alder along these water courses insures significant litter inputs.

Table 2. Spearman rank correlations between abundances of macro-invertebrate taxa and the first two principal components derived from the summer 1984 leaf-pack experiment. The functional group assigned to each taxon are shown: SH-shredder; FP-fine particle feeder; CO-gathering or filtering collector; P-predator; U-unknown.

| Taxon | Functional group | Spearman rank correlation |
|---|---|---|
| Factor 1 - 27.9% of total variance<br>- characterizes communities dominated by fine particle feeders | | |
| ostracods | FP | 0.722 *** |
| cyclopoid copepods | FP | 0.682 *** |
| Polycentropodidae (caddisfly) | U | 0.662 *** |
| Oligochaeta (worm) | FP | 0.691 *** |
| *Paraleptophlebia* (mayfly) | CO | 0.606 *** |
| Planorbidae (snails) | FP | 0.594 *** |
| harpactacoid copepods | FP | 0.578 *** |
| *Nemoura* (stonefly) | SH | 0.544 ** |
| Ceratopogonidae (no-see-um) | CO/FP | 0.490 ** |
| chironomid midges | CO/FP | 0.422 * |
| water mites | P | -0.351 * |
| *Ameletus* (mayfly) | SH | -0.422 * |
| Factor 2 - 25.2% of total variance<br>- collectors +ve loadings, large-bodied shredders -ve loadings | | |
| *Ephemerella* (mayfly) | CO | 0.859 *** |
| Lepidostomtidae (caddisfly) | SH | 0.778 *** |
| *Baetis* (mayfly) | CO | 0.766 *** |
| *Alloperla* (stonefly) | P | 0.760 *** |
| *Capnia* (stonefly) | SH | 0.758 *** |
| chironomid midges | CO/FP | 0.745 *** |
| Empididae (dance-flys) | U | 0.691 *** |
| *Nemoura* (stonefly) | SH | 0.605 *** |
| *Asellus* (isopod) | SH | -0.752 *** |
| *Anisogammarus* (amphipod) | SH | -0.780 *** |

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

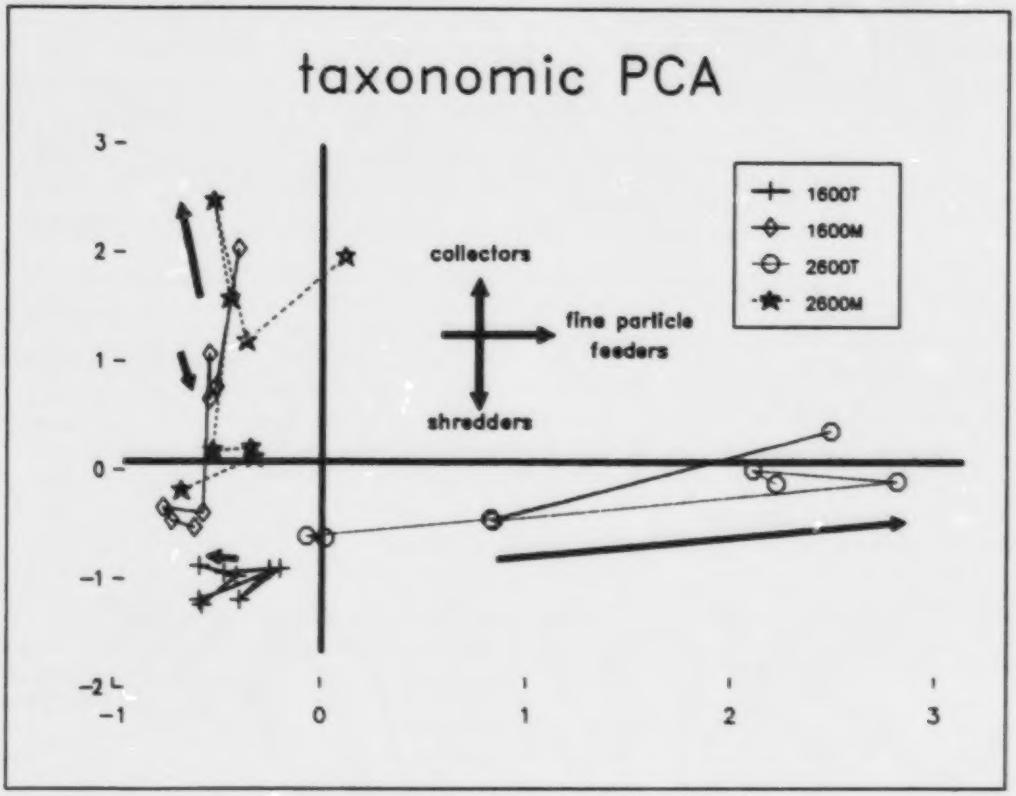


Figure 9. PCA analysis of taxonomic composition of leaf pack invertebrates during the summer of 1984. The 1 wk period that includes the application of herbicide at 1600T is indicated.

In comparison, features that would retain fine detritus in the main-stem, deep pools, debris jams and complex channel form, are deteriorating rapidly in the aftermath of clear-cut logging, probably significantly reducing the capacity of the main-stem to capture and process detritus, and increasing the relative importance of the valley-bottom tributaries as sites of energy capture.

In Carnation Creek there are indications that detrital processing in valley-bottom tributaries does serve as an important energy source for the main-stem animal community. Water flowing out of the tributaries is considerably richer in fine particulate organic matter than water in the main-stem (Holtby and Baillie, unpubl. data). Those particles are undoubtedly collected by the numerous invertebrates in the main-stem adapted to the collection of fine particles. The probable importance of this detrital input to the fish community is suggested by the concentrations of subyearling coho immediately downstream of the tributary inflows (Fig. 10) where densities can be as much as 2.5 times higher than in areas far removed from tributary influences.

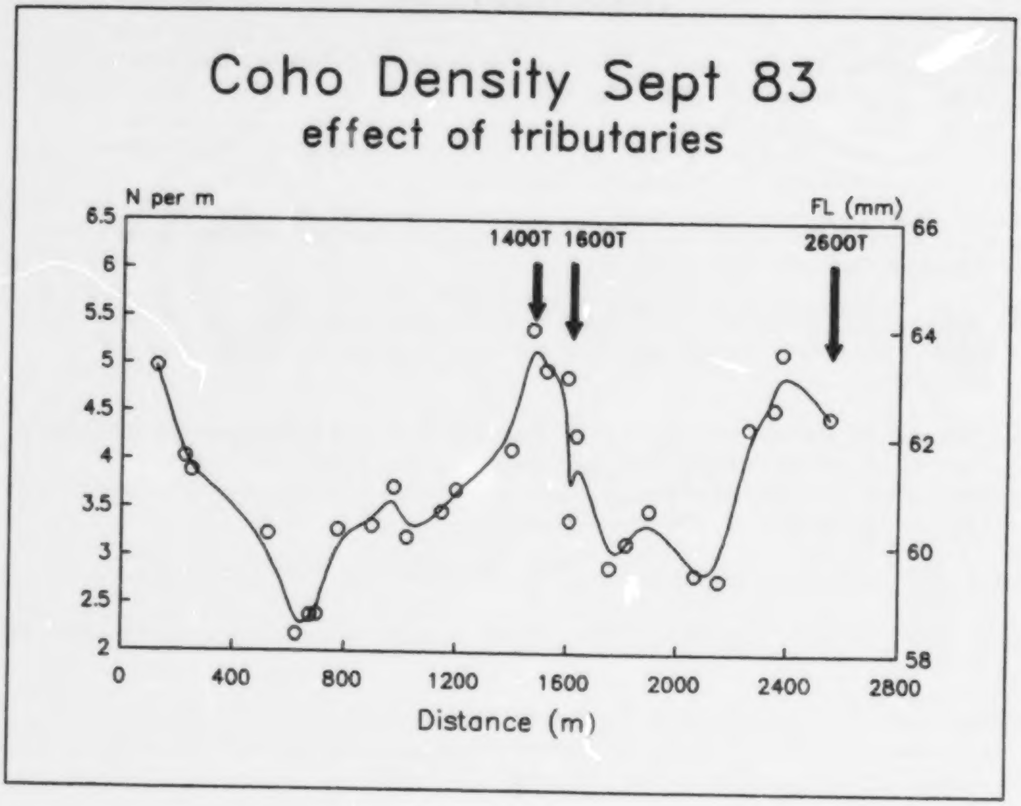


Figure 10. The variation of estimated fish densities down the length of Carnation Creek in Sept. 1983. The locations of the confluences of the main-stem with important valley-bottom tributaries are indicated.

We were unable to detect any changes in the either the invertebrate community of the tributary or the salmonids in the tributary after herbicide application (Holtby and Baillie 1989). However, we did observe large decreases in detrital inputs to the tributary and changes in the composition of detrital particles in the tributary sediments. Those changes, coupled with the probable significance of the tributary to the energy budget of the entire system, recommend caution in future modifications to the riparian vegetation of valley-bottom tributaries.

## ACKNOWLEDGEMENTS

Our study was made possible by a contract to S.J. Baillie and an operating grant to L.B. Holtby from the Forest Resource Development Agency, administered through the British Columbia Ministry of Forests and the Canadian Forestry Service. This study was part of the Carnation Creek Experimental Watershed Project, a multi-disciplinary forestry-fishery study funded by the Canadian Dept. of Fisheries and Oceans, the Canadian Forestry Service, Atmospheric Environment Service and Inland Waters Directorate of Environment Canada, the B.C. Ministry of Forests, the B.C. Ministry of Environment and MacMillan Bloedel Ltd. Thanks to A. Hirst, D. Leahy, and B. Andersen who assisted in sample collection.

## LITERATURE CITED

Andersen, B.A. 1984. Fish populations of Carnation Creek and other Barkley Sound streams 1981-1982. Can. Data Rep. Fish. Aquat. Sci. 435: 63 p.

Andersen, B.A. 1985. Fish populations of Carnation Creek and other Barkley Sound streams 1983-1984. Can. Data Rep. Fish. Aquat. Sci. 553: 62 p.

Andersen, B.A. 1987. Fish populations of Carnation Creek and other Barkley Sound streams 1985-1986. Can. Data Rep. Fish. Aquat. Sci. 657: 59 p.

Boling, R.H. Jr., E.D. Goodman, J.A. Van Sickle, J.O. Zimmer, K.W. Cummins, R.C. Petersen and S.R. Reice. 1975. Toward a model of detritus processing in a woodland stream. Ecol. 56:141-151.

Culp, J.M and R.W. Davies. 1982. Effect of substrate and detritus manipulation on macroinvertebrate density and biomass: implications for forest clearcutting. pp. 210-216 In G.F. Hartman (ed.) Proceedings of the Carnation Creek Workshop: a ten-year review. Pacific Biol. Sta., Nanaimo, B.C. V9R 5K6. 404 p.

Cummins, K.W. 1974. Structure and function of stream ecosystems. BioScience 24:631-641.

Cummins, K.W. and M.J. Klug. 1979. Feeding ecology of stream invertebrates. Ann. Rev. Ecol. Syst. 10:147-172.

Cummins, K.W., G.L. Spengler, G.M. Ward, R.M. Speaker, R.W. Ovink, D.C. Mahan and R.L. Matingly. 1980. Processing of confined and naturally entrained leaf litter in a woodland stream ecosystem. Limnol. Oceanogr. 25:952-957.

Dixon, K.R. 1976. Analysis of seasonal leaf fall in north temperate deciduous forests. Oikos 27:300-306.

Fisher, S.G. and G.E. Likens. 1972. Stream ecosystem: organic energy budget. BioScience 22:33-35.

Holtby, L.B. 1989. Changes in the temperature regime of a valley-bottom tributary of Carnation Creek, British Columbia, oversprayed with the herbicide ROUNDUP. This proceedings.

Holtby, L.B. and S.J. Baillie. 1989. Effects of the herbicide ROUNDUP on coho salmon fingerlings of an oversprayed tributary of Carnation Creek, B.C. This proceedings.

Hynes, H.B.N. 1963. Imported organic matter and secondary productivity in streams. Proc. XVI Int. Congr. Zool. 3:324-329.

Kaushik, N.K. and H.B.N. Hynes. 1971. The fate of dead leaves that fall into streams. Arch. Hydrobiol. 68:465-515.

Neaves, P.I. 1978. Litter fall, export, decomposition, and retention in Carnation Creek, Vancouver Island. Fish. and Mar. Serv. Tech. Rep. No. 809. 45 p.

Petersen, R.C. and K.W. Cummins. 1974. Leaf processing in a woodland stream. Freshwat. Biol. 4:343-368.

Reice, S.R. 1980. The role of substratum in benthic macroinvertebrate microdistribution and litter decomposition in a woodland stream. Ecol. 61:580-590.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. Overview of Carnation Creek herbicide project: historical perspective, experimental protocols and spray operations. This proceedings.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37:130-137.

Webster, J.R. and J.B. Waide. 1982. Effects of forest clearcutting on leaf breakdown in a southern Appalachian stream. Freshwat. Biol.12: 331-344.

# DRIFT OF AQUATIC INVERTEBRATES IN A GLYPHOSATE CONTAMINATED WATERSHED

D.P. Kreutzweiser and P.D. Kingsbury

Canadian Forestry Service
Forest Pest Management Institute
P.O. Box 490, Sault Ste. Marie
Ontario, P6A 5M7

## ABSTRACT

Short-term effects on stream invertebrates of glyphosate applications to parts of the Carnation Creek watershed were determined by measuring drift response. Drift densities of most invertebrates did not increase in response to the glyphosate applications. Post-spray mean drift values were not significantly higher (ANOVA $p > 0.05$) than pre-spray mean densities. A non-significant but measurable alteration in drift patterns of *Paraleptophlebia* sp. (Ephemeroptera) suggested a slight and ephemeral drift response to glyphosate contamination by this specific may-fly genus. A small post-spray increase in the numbers of drifting *Gammarus* sp. (Amphipoda) was less conclusive.

## INTRODUCTION

As part of research activities (Reynolds et al. 1989) conducted to investigate the fate and effects of a glyphosate application to the Carnation Creek valley, we examined the short-term effects on aquatic invertebrates by measuring drift response. A program to determine the fate and persistence of the herbicide in stream water was jointly conducted with this project, but results from residue analyses are presented elsewhere (Feng et al. 1989).

Three sites were selected for sampling invertebrate drift: 1) in the main channel of Carnation Creek approximately 30 m below B-Weir and downstream of most treated portions of the valley, 2) in C-Creek, a 1000 m ephemeral tributary buffered from the applications, and 3) in 1600 tributary, a 800 m stream directly oversprayed (Fig. 1). Samples from the tributaries were collected approximately 10 m upstream from their confluences with the main channel. The drift site below B-weir was typical of most of lower Carnation Creek, with a section of riffle approximately 4 m wide comprising scoured gravel with small amounts of sand and silt. Water velocity ranged from 0.55 to 1.15 m/sec during sample collection. Water levels in C-Creek fluctuated drastically throughout the sampling period such that the drift site varied from 0.5 m wide with almost no flow to 2 m wide with a water velocity of 0.97 m/sec. The stream bottom at the C-Creek sampling site and through most of the 100 m section bordering the spray blocks consisted of small rubble and gravel with patches of sand and silt in quieter areas. Although riparian vegetation was dense in certain sections, C-Creek contained little organic debris. The 1600 tributary drained a swampy portion of the valley south of the main channel with a number of small pools and sections of moderate flow in constricted areas. In contrast to the other two sampling sites, this tributary contained a large amount of organic debris with a bottom type mostly consisting of silt, detritus, sand and small sections of fine gravel. The drift sampling site in 1600 tributary was approximately 0.5 m wide with a flow rate that varied much less (0.33 to 0.58 m/sec) than the main channel or C-Creek.

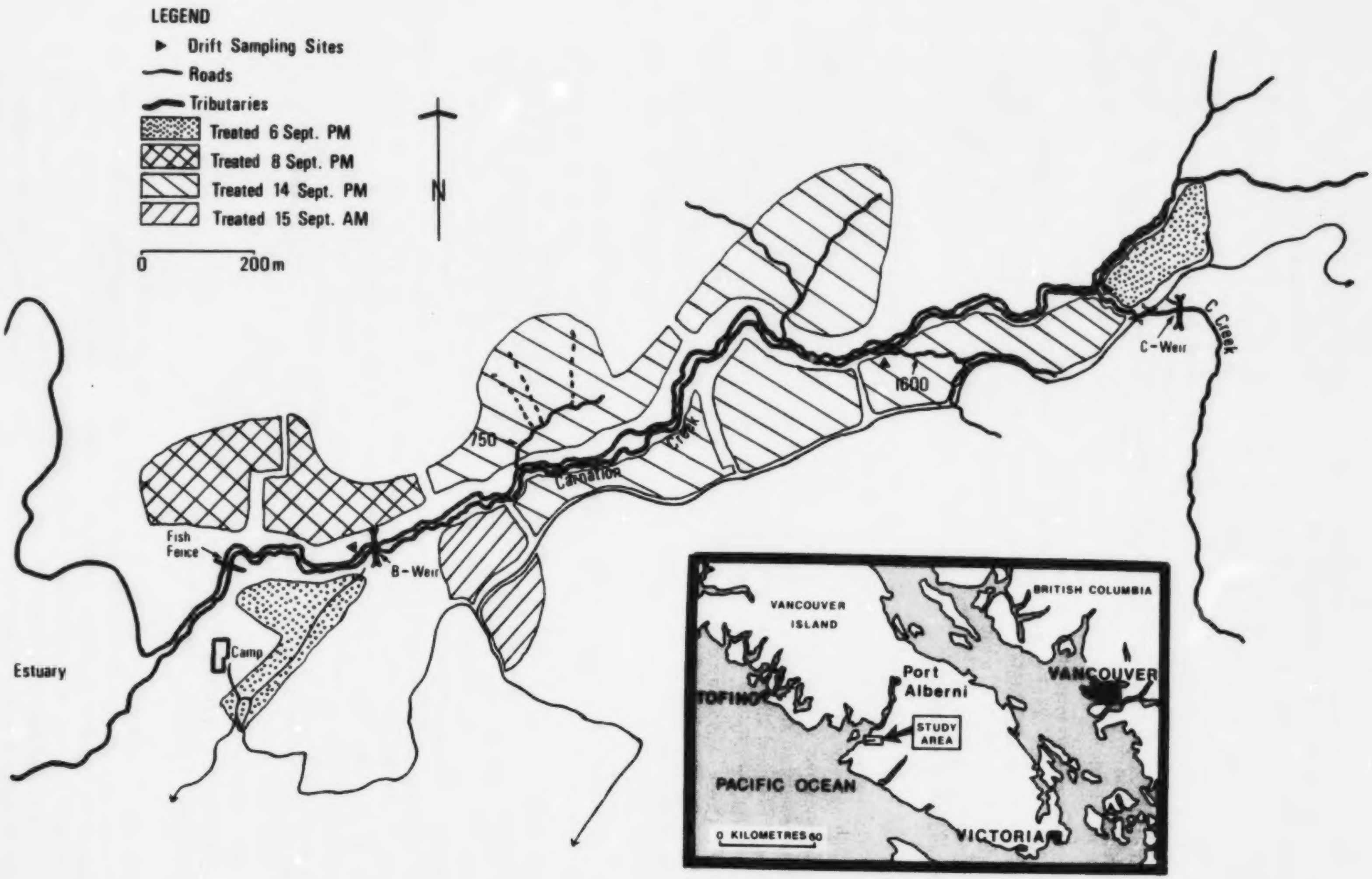

LEGEND
▶ Drift Sampling Sites
Roads
Tributaries
Treated 6 Sept. PM
Treated 8 Sept. PM
Treated 14 Sept. PM
Treated 15 Sept. AM
0
200 m
N
C Creek
C-Weir
1600
750
Carnation
Creek
B-Weir
Fish Fence
Camp
Estuary
BRITISH COLUMBIA
VANCOUVER ISLAND
Port Alberni
VANCOUVER
TOFINO
STUDY AREA
PACIFIC OCEAN
VICTORIA
0 KILOMETRES 60

Figure 1. Glyphosate treatment blocks and drift sampling sites in the Carnation Creek watershed, September 1984.

A specific drift net location was established at each site and used throughout the sampling period. Drifting invertebrates were collected in 0.47 x 0.32 m nets with a 363 $\mu$ mesh positioned midstream to sample a water column from the surface to the stream bottom, or to the net bottom when water levels exceeded the height of the net opening. Current velocity and depth of water at the net opening were measured with each sample, and the collected invertebrates were subsequently quantified as number per 10 $m^3$ of water flowing through the drift net. Drift samples of 5 to 15 min duration were taken hourly during sunset and sunrise periods on collection dates, corresponding to the times when stream invertebrate drift normally peaks and declines (Waters 1972). Additional samples were collected at hourly intervals immediately following the applications of herbicide.

Differences in drift levels between sample periods were tested with ANOVA ($p < 0.05$). Because of the small size of the creeks, especially C-Creek and 1600 tributary, spatial replication of drift nets was impossible. The values tested were mean drift numbers from collections over equal periods of time (i.e. means from morning or evening drift periods). Mean values were tested for statistical significance, but peak drift numbers provided a clearer indication of drift magnitude, and are presented.

Glyphosate was applied as ROUNDUP (30.5% active ingredient) at a concentration of 2.0 kg a.i./ha in a total volume of 258 L/ha using a MICROFOIL BOOM with 1.5 mm hayrack nozzles, mounted on a Bell G-47 helicopter (Reynolds et al. 1989). Glyphosate was applied to 11 spray blocks (Fig. 1) at various times over four separate days. Only those with potential for contaminating the portion of the watershed above drift sampling sites are discussed. On the evening of 6 September 1984, between 1940 and 2005 h, a spray block immediately adjacent to the east edge of C-Creek was treated with herbicide (Fig. 1). Most of the remaining creek valley, including the portion on the west side of C-Creek, was sprayed between 1425 and 1945 h on 14 September. The main channel of Carnation Creek and C-Creek were buffered by a 10 m no-spray zone, while 1600 tributary was intentionally oversprayed.

## RESULTS AND DISCUSSION

Drift densities of most aquatic invertebrates did not increase in response to the glyphosate applications. None of the post-spray mean drift values for total invertebrate catches were significantly higher than pre-spray mean densities ($p > 0.05$). Since many of the organisms in the drift samples were collected in low numbers, only the more frequently collected taxa are listed with their peak drift levels (Table 1). High water conditions at both the beginning (from heavy rains on 4 September) and end (from heavy rains on evening of 15 September) of the sampling period probably accounted for most of the variations in total drift density. Some groups, such as *Baetis* sp. at B-Weir and *Capnia* sp. in C-Creek, demonstrated increases in drift rate after an application, but the levels were comparable to previous pre-spray evening drifts. Several other taxa, including *Lepidostoma* sp. at B-Weir and early instar limnephilid caddisflies in 1600 tributary, showed an increase in drift density at the end of the sampling period that corresponded to heavy rainfall and an approximately five-fold increase in stream discharge. However, elevated drift levels of these same groups were found in high water conditions at the beginning of the study period (September 4), suggesting that the post-spray increases resulted from the increased discharge rather than glyphosate contamination.

Although the drift patterns of most invertebrates were not measurably affected by the herbicide treatment, the drift response of *Gammarus* sp. and *Paraleptophlebia* sp. suggests some disturbance of these genera by the glyphosate contamination. None of the mean post-spray drift densities of these two taxa were significantly higher than mean pre-spray densities ($p > 0.05$), but a measurable alteration in drift patterns, especially of *Paraleptophlebia*, was demonstrated. These drift increases may have resulted from natural causes, but were coincident with glyphosate contamination and therefore cannot be dismissed as being unrelated to the herbicide applications.

*Gammarus* sp. in 1600 tributary drifted in numbers approximately twice as high on the evening of the overspray as they were in pre-spray evening drifts (Table 1). This amphipod is commonly found in stream drift but is not particularly susceptible to glyphosate. Folmar et al. (1979) reported a 48 h $EC_{50}$ of 43,000 $\mu g/L$ for *Gammarus* exposed to ROUNDUP contaminated water. The highest glyphosate concentration measured in 1600 tributary was 162 $\mu g/L$ (Feng et al. 1989). Although the magnitude of the drift increase was little more than measurable and the duration was less than two hours, the elevated drift on the evening of the application represents a disruption of the previously established evening drift pattern and may indicate a disturbance of *Gammarus* sp. by glyphosate contamination in 1600 tributary. Definite indications of a toxic or behavioral response of *Gammarus* sp. to the herbicide application are precluded by the minimal drift increase.

Immediately following the herbicide treatment to the eastern periphery of C-Creek on 6 September, the numbers of drifting *Paraleptophlebia* sp. distinctly increased (Table 1). The mean number of these mayflies on the evening of the adjacent application was not significantly different from the previous evening ($p > 0.05$), but as illustrated in Figure 2, the drift rate attained a higher level (approximately 10x the pre-spray peak) than at any other time in C-Creek.

*Paraleptophlebia* sp. drift rates in C-Creek did not increase with treatment of the other adjacent spray block on 14 September. A 10 m buffer on both sides of C-Creek was observed for both applications adjacent to the creek, but recorded field observations suggested that the helicopter flew closer to the creek on the evening of 6 September than during the 1600 tributary overspray on 14 September. During the first application adjacent to C-Creek, the aircraft flew a spray pattern roughly parallel to the stream and given the circuitous nature of the creek, the likelihood of inadvertently overspraying parts of C-Creek was greater than when flight patterns approached the creek at right angles during the application on 14 September. The greater opportunity for contamination of the stream during the first peripheral application may account for the differential response of *Paraleptophlebia* sp. to the two applications adjacent to C-Creek. Since no residue samples were collected from C-Creek, the contamination cannot be substantiated.

This mayfly also demonstrated an increased drift rate in 1600 tributary and B-Weir in evening drift samples 30 h after the overspray of 1600 tributary (Fig. 2). The increases were less than 9x the pre-spray peak and may simply have been a response to the increase in stream discharge resulting from heavy rainfall during the evening sampling period. However, elevated drift levels of *Paraleptophlebia* sp. at these two sites were not previously associated with the high water conditions at the beginning of the study period 4-5 September (Fig. 2). The post-spray drift increases following the rain storm indicate a response to glyphosate contamination from runoff. Shortly after rain began on 15 September, concentrations of glyphosate in stream water increased at both B-Weir and 1600 tributary (Feng et al. 1989). The occurrence of glyphosate residues may have combined with the effects of increasing discharge to produce these slightly elevated drift levels of *Paraleptophlebia* sp.

The apparent response of *Paraleptophlebia* mayflies to the glyphosate applications suggests a particular susceptibility of this genus to the herbicide. If the drift response in C-Creek was attributable to the herbicide treatment, the impact was limited to *Paralephophlebia* since none of the other groups demonstrated a similar increase. The indications of a slight post-spray increase in drifting *Gammarus* sp. were inconclusive. In summary, glyphosate was applied at operational rates to or near Pacific salmon nursery streams and resulted in, at most, slight and ephemeral drift increases of one mayfly genus.

Table 1. Drift of selected aquatic invertebrates (no. per 10 $m^3$) collected in Carnation Creek. Values for each taxon represent peak numbers collected in morning or evening drift samples. Totals represent the total numbers of all taxa in the largest of hourly samples from morning or evening sample period

| Date (September) collection time | 5 PM | 6 AM | 6 PM | 7 AM | 11 PM | 12 PM | 13 AM | 14 PM | 15 AM | 15 PM |
|---|---|---|---|---|---|---|---|---|---|---|
| C Creek* | | | | | | | | | | |
| *Baetis* sp. | 15.5 | 11.4 | 12.2 | 2.5 | 2.9 | 0.4 | 0 | 2.2 | 0 | 0 |
| *Paraleptophlebia* sp. | 2.0 | 1.4 | 21.9 | 1.2 | 1.1 | 0 | 0 | 2.2 | 0 | 0.9 |
| *Amphinemeura* sp. | 4.0 | 4.3 | 2.4 | 1.2 | 0.7 | 0.4 | 0 | 0 | 0 | 0.4 |
| *Capnia* sp. | 1.3 | 4.3 | 4.9 | 0 | 0.7 | 0.8 | 0 | 4.3 | 0 | 0.2 |
| *Limnephilidae* (early instar) | 2.7 | 1.4 | 0 | 2.5 | 0 | 1.3 | 0 | 0 | 0 | 1.9 |
| TOTAL | 33.8 | 22.8 | 43.9 | 7.4 | 7.3 | 4.0 | 0 | 6.5 | 1.4 | 6.1 |
| 1600 Tributary** | | | | | | | | | | |
| *Paraleptophlebia* sp. | 0.9 | 0 | 0.9 | 0 | 0.7 | 0.7 | 0 | 0.8 | 0 | 7.4 |
| *Amphinemeura* sp. | 0.9 | 0.9 | 2.0 | 0 | 0.7 | 0 | 0 | 0.8 | 0 | 0.9 |
| *Limnephilidae* (early instar) | 8.2 | 10.4 | 6.1 | 7.5 | 3.0 | 3.0 | 2.6 | 1.5 | 0.9 | 4.8 |
| *Chironomidae* | 7.1 | 1.7 | 1.0 | 2.8 | 3.5 | 3.0 | 1.3 | 1.5 | 0.9 | 3.3 |
| *Gammarus* sp. | 7.1 | 6.0 | 2.7 | 4.7 | 3.8 | 7.5 | 4.0 | 12.4 | 3.0 | 18.2 |
| TOTAL | 18.8 | 13.9 | 7.1 | 9.3 | 7.1 | 13.5 | 7.9 | 15.5 | 3.0 | 33.5 |
| B-Weir | | | | | | | | | | |
| *Baetis* sp. | 19.4 | 24.2 | 21.4 | 16.9 | 35.4 | 38.5 | 4.3 | 42.6 | 3.6 | 29.4 |
| *Paraleptophlebia* sp. | 3.6 | 4.4 | 1.0 | 1.6 | 1.4 | 1.9 | 0 | 0.5 | 0.3 | 15.5 |
| *Alloperla* sp. | 1.5 | 1.9 | 0.5 | 0.5 | 1.9 | 2.7 | 0.1 | 3.4 | 0 | 1.9 |
| *Amphinemeura* sp. | 3.8 | 1.1 | 1.6 | 1.3 | 0.2 | 1.4 | 0 | 0.5 | 0 | 1.9 |
| *Capnia* sp. | 5.2 | 2.0 | 3.6 | 2.9 | 7.4 | 8.1 | 1.4 | 11.8 | 0.3 | 6.4 |
| *Lepidostoma* sp. | 43.7 | 12.7 | 8.6 | 1.9 | 0.5 | 8.4 | 1.6 | 1.0 | 0.3 | 19.6 |
| *Limnephilidae* (early instar) | 2.6 | 2.3 | 1.4 | 0.8 | 0.7 | 1.4 | 2.2 | 0.5 | 0.3 | 5.4 |
| *Chironomidae* | 6.5 | 2.5 | 4.2 | 2.4 | 1.4 | 6.1 | 1.4 | 2.4 | 0.5 | 7.8 |
| *Dixidae* | 1.4 | 1.3 | 0.4 | 0.8 | 0 | 0.5 | 0.3 | 0.5 | 0 | 6.4 |
| *Simuliidae* | 1.2 | 1.1 | 3.6 | 1.1 | 0.9 | 0.4 | 0.5 | 1.0 | 0.3 | 0.3 |
| TOTAL | 88.4 | 55.1 | 47.2 | 32.8 | 51.2 | 65.0 | 12.7 | 63.7 | 4.4 | |

* East periphery sprayed at 1940 h to 2000 h on 6 September and west periphery sprayed at 1515 h to 1535 h on 14 September 1984.

** Oversprayed at 1425 h to 1510 h on 14 September 1984.

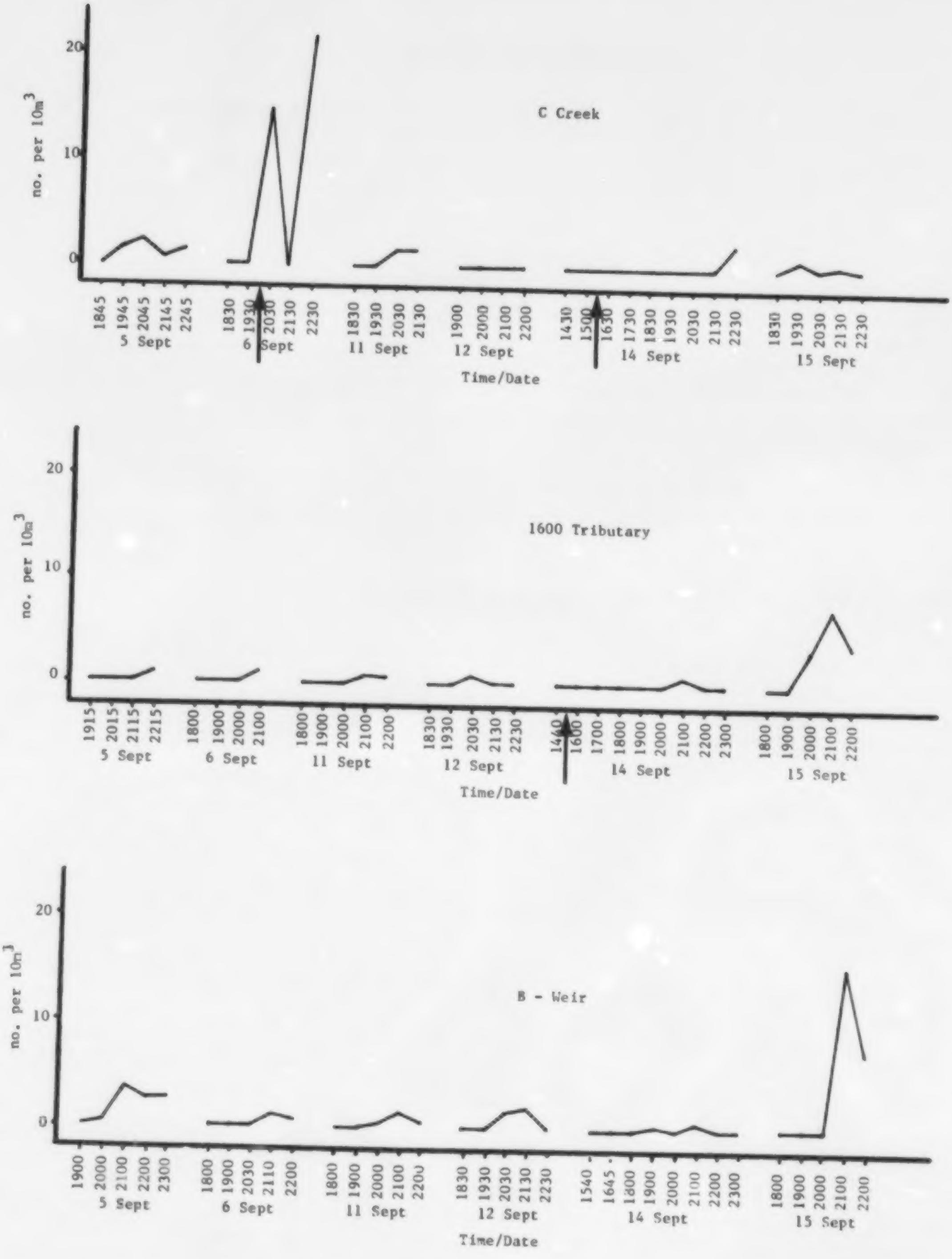


Figure 2. *Paraleptophlebia* sp. drift densities in Carnation Creek and two tributaries during evening sampling hours. Arrows indicated time of glyphosate applications.

## ACKNOWLEDGEMENTS

The contributions to this study by P. Reynolds, Project Coordinator, are greatly appreciated. The cooperation, assistance, and provision of equipment and facilities by the Pacific Biological Station, Nanaimo, B.C. were vital to the operations of the program and are gratefully acknowledged. A major portion of this research was funded by the B.C. Ministry of Forests.

## REFERENCES

Feng, J.C., D.G. Thompson and P.E. Reynolds. 1987. Fate of glyphosate in a forest stream ecosystem. This proceedings.

Folmar, L.C., H.O. Sanders and A.M. Julin. 1979. Toxicity of the herbicide glyphosate and several of its formulations to fish and aquatic invertebrates. Arch. Environ. Contam. Toxicol. 8:269-278.

Reynolds P.E., J.C. Scrivener, L.B. Holtby, P.D. Kingsbury. 1989. Overview of Carnation Creek herbicide project: historical perspective, experimental protocols, spray operations. This proceedings.

Waters, T.F. 1972. The drift of stream insects. Ann. Rev. Entomol. 17:258-272.

# SALMONID TOXICITY STUDIES WITH ROUNDUP

Peter M. Chapman

E.V.S. Consultants
195 Pemberton Avenue
North Vancouver, B.C.
V7P 2R4

## ABSTRACT

Laboratory toxicity studies were conducted to assess acute lethal toxicity of ROUNDUP herbicide to three salmonid species (rainbow trout, chinook and coho salmon), and acute sublethal toxicity to coho salmon in seawater challenge tests. The results of this testing indicate that, during the course of normal usage at the manufacturer's recommended use-rates, ROUNDUP poses no acute toxicity hazard to salmonids nor will it affect seawater adaptation of coho salmon.

## INTRODUCTION

This manuscript summarizes published (Mitchell et al. 1987a; b) and unpublished research into the acute toxicity of ROUNDUP herbicide. Unlike most of the other studies reported in these Proceedings, the present research was not part of work done at Carnation Creek. Rather, this research was funded by Monsanto (St. Louis, U.S.A.) to answer specific questions concerning the aquatic toxicity of ROUNDUP.

The results of this research were the subject of an invited platform presentation at the Carnation Creek Workshop in 1987 and are published here due to their relevance to the Carnation Creek Project. Two separate studies were conducted: determinations of acute lethality using standard 96-h $LC_{50}$ bioassay testing, and seawater challenge testing to determine whether ROUNDUP has an effect on seawater adaptation of anadromous salmonids.

## MATERIALS AND METHODS

Full details of the materials and methods used are provided in Mitchell et al. (1987a, b) and are briefly summarized below.

### Acute Lethality

Acute lethality (96-h $LC_{50}$) static bioassay testing was conducted in accordance with procedures outlined by APHA (1985) using three different salmonid species: rainbow trout *(Salmo gairdneri)*, chinook salmon *(Oncorhynchus tshawytscha)* and coho salmon *(O. kisutch)*. Three different waters were used in testing: dechlorinated North Vancouver City drinking water, dechlorinated reconstituted North Vancouver City drinking water, and water collected from Cultus Lake, B.C.

Test conditions were: ten fish per concentration, loading densities below 1.0 g/L, 200 L fiberglass tanks for the coho and chinook, 20 L glass tanks for the trout, 11 ± 10°C, a 16 h light: 8 h dark photoperiod regime, and dissolved oxygen maintained at greater than 60% saturation.

Tests were conducted by directly diluting ROUNDUP to obtain the desired exposure concentrations. Exposure concentrations were confirmed by selective HPLC analyses of the bioassay waters. Median lethal values (96-h $LC_{50}$s) and 95% confidence limits were calculated from survival data using probit, moving-average or binomial probability analysis, and were confirmed by graphical log-probit analysis.

### Seawater Challenge

Coho salmon smolts were exposed to three sublethal concentrations of ROUNDUP following the experimental design shown in Figure 1. Seawater challenge testing was conducted on half of the test fish immediately after the 10-d test exposure: the remaining fish were kept in clean water for 10-d prior to seawater challenge to allow detection of any delayed results. At the end of both sets of seawater challenge testing, the fish were sacrificed for $Na^+$ analysis.

Test conditions were: flow-through systems, dechlorinated North Vancouver City drinking water; 200 L fiberglass tanks; water flow rates of 1.0 L/min (95% molecular replacement time of 9 h); fish fed *ad libitum;* 11 ± 1°C; 16 h light: 8 h dark photoperiod with 1 h gradual dawn/dusk simulation. Na+ was measured using atomic emission spectophotometry with appropriate quality assurance/quality control procedures. The length, weight, hematocrit values (percent blood cells by volume), and condition factor (100 times weight divided by length cubed) of each fish was also determined.

Tests were conducted by directly diluting ROUNDUP to obtain the desired exposure concentrations. Exposure concentrations were confirmed by selective HPLC analyses of the bioassay waters. Mean results for herbicide-exposed fish for Na+, hematocrit, condition factor, length and weight were statistically compared with the mean results for control fish using a one-way analysis of variance with specific differences determined using Dunnett's method (Miller 1966).

## RESULTS AND DISCUSSION

### Acute Lethality

The results of acute lethality testing are presented in Table 1 in terms of both the total ROUNDUP formulation and the IPA salt of glyphosate. Test concentrations were confirmed by glyphosate analysis. After 24 h, 70-87% of target levels remained in the fiberglass tanks while only 21-63% remained in the glass tanks. The reason(s) for this difference are unknown but may relate to different rates of herbicide absorption on fiberglass as compared to glass. However, since there were no significant differences in toxicity related to the differences in remaining glyphosate levels, it appears that the majority of the lethal dose was absorbed by the fish prior to any major loss from solution.

As is apparent from Table 1, there were no significant differences in toxicity to 0.37 g trout, 4.6 g chinook and 11.8 g coho. Similarly, there was no significant difference in toxicity with dilution water type. These results contrast with those of Folmar et al. (1979), who reported large, significant differences in toxicity when testing was done at pH 6.5 as compared to pH 7.5, and with trout weighing 2.0 g as compared to trout weighing 1.0 g. Folmar et al's (1979) results are unexpected given the small changes in test pH and fish size and are not supported by the present study or by work done by Hildebrand et al. (1982). These latter authors found that differing water type and conductivity did not affect toxicity.

FIGURE 1. SCHEMATIC REPRESENTATION OF SEAWATER CHALLENGE TESTING.

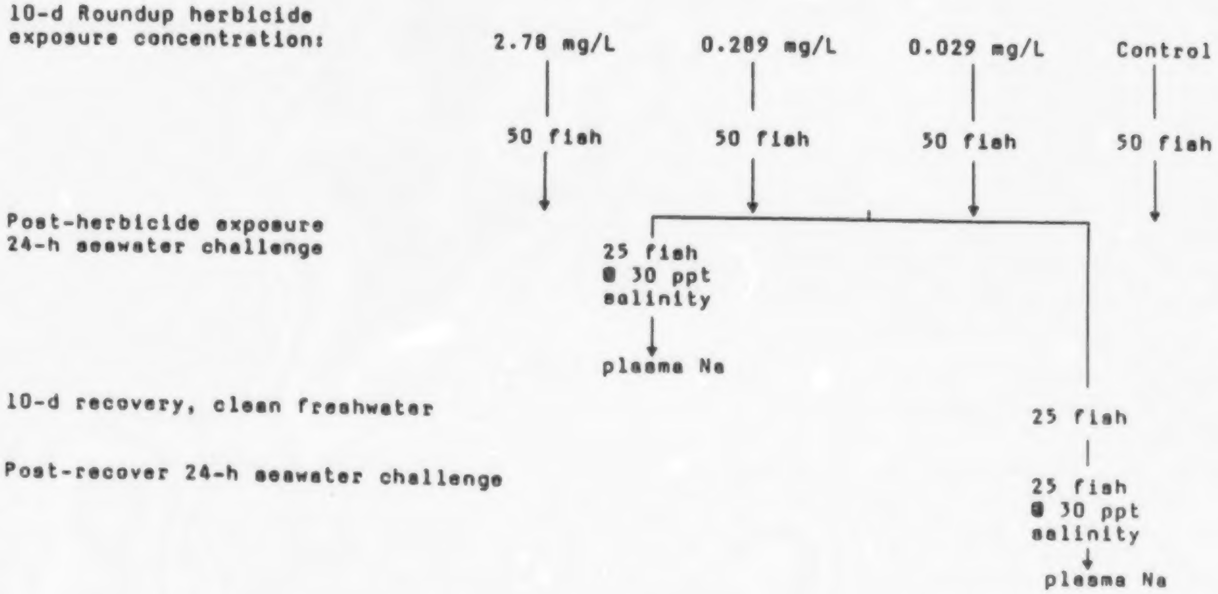

10-d Roundup herbicide exposure concentration:
2.78 mg/L
0.289 mg/L
0.029 mg/L
Control
50 fish
50 fish
50 fish
50 fish
Post-herbicide exposure 24-h seawater challenge
25 fish @ 30 ppt salinity
plasma Na
10-d recovery, clean freshwater
25 fish
Post-recover 24-h seawater challenge
25 fish @ 30 ppt salinity
plasma Na

Figure 1. Schematic representation of seawater challenge testing.

Table 1. Results of acute lethality testing.

| Weight (g) | Water type[a] | Total formulation[b] (mg/L) | IPA salt of glyphosate[b] (mg/L) | Source |
|---|---|---|---|---|
| Rainbow trout | | | | |
| 0.37 | dechl. | 26<br>(12-38) | 12<br>(6-18) | This study |
| 0.37 | recons. | 22<br>(12-38) | 11<br>(6-18) | This study |
| 0.37 | lake | 15<br>(12-21) | 7<br>(6-10) | This study |
| 1.4 | dechl. | 55<br>(50-60) | n.d. | Hildebrand *et al.* 1982 |
| 1.6 | stream | 52<br>(n.d.) | n.d. | Hildebrand *et al.* 1982 |
| 2.0 | recons. | n.d. | 8<br>(7-10) | Folmar *et al.* 1979 |
| Chinook | | | | |
| 4.6 | dechl. | 20<br>(17-27) | 10<br>(8-13) | This study |
| Coho | | | | |
| 11.8 | dechl. | 22<br>(12-38) | 11<br>(6-18) | This study |

[a] Dechl. = dechlorinated, recons. = reconstituted
[b] Values in parentheses are 95% confidence limits
n.d. = no data

## Seawater Challenge

The purpose of seawater challenge testing was to evaluate the potential sublethal toxicity of ROUNDUP. Sublethal toxicity was tested by using the sensitive seawater entry phase of the anadromous salmonid life-cycle. Seawater entry is a sensitive time when high natural mortality occurs due to the physiological stress imposed by adjusting from fresh to salt water (Clarke 1982). Since additional stress would be expected to increase mortalities, the question was asked: is seawater adaptation affected by ROUNDUP?

The adaptive process of smoltification is complex. The main adaptation provided is an active increase in salt excretion capacity. The efficiency of salt regulation can be measured by seawater challenge testing, which determines the concentration of Na+ in fish plasma following a 24-h seawater exposure. Fish with plasma levels greater than 170 meg/L grow more slowly, have reduced locomotor performance, and increased susceptibility to predation (Wedemeyer *et al.* 1980).

The results of seawater challenge testing are presented in Table 2. There was no effect on seawater adaptation of coho salmon due to ROUNDUP. Plasma sodium values were all less than 170 meg/L and were not significantly different from the controls. Survival values were between 95 and 100%. There were no significant differences between test and control values for hematocrit, condition factor, length and weight. There were no apparent behavioral abnormalities; the fish fed normally and gained weight during the test.

Table 2. Results of seawater challenge testing.

| Herbicide treatment (mg/L) | n | Plasma Na+ (meg/L) | Hematocrit[a] (%) | Condition factor[b] |
|---|---|---|---|---|
| Post-herbicide | | | | |
| 0.029-2.78[c] | 24-25 | 155-158 | 36-39 | 0.95-0.98 |
| Control | 23 | 159 | 40 | 0.97 |
| Post-recovery | | | | |
| 0.029-2.78 | 22-24 | 160-162 | 42-47 | 0.96-1.00 |
| Control | 25 | 160 | 45 | 0.99 |

[a] Hematrocrit values = percent red blood cells by volume.
[b] Condition Factor = 100 x weight/length cubed.
[c] The range of values obtained for three test concentrations (0.029, 0.289 and 2.78 mg/L) are shown.

As summarized by Mitchell *et al*. (1987b), disruption of seawater adaptation has been shown to occur following sublethal toxicant exposure to heavy metals, low pH, contaminated sediments and fish disease therapeutic agents. Previous studies with other herbicides have shown no effects on seawater adaptation at concentrations of up to 0.16X the 96-h $LC_{50}$ value.

## CONCLUSIONS

### Acute Lethality

The toxicity values derived in the present study are generally within the range of previously determined values; the full range of values for 96-h $LC_{50}$s to salmonids (Table 1) is from 15 to 55 mg/L based on the total formulation. Since the Maximum Environmental Concentration of the total formulation measured following aerial application at the manufacturer's recommended use-rates is 0.27 mg/L (Newton *et al*. 1984), no acute ROUNDUP toxicity hazard to salmonids is expected during the course of this product's normal usage.

### Seawater Challenge

The maximum exposure concentration of ROUNDUP used in seawater challenge testing was 2.78 mg/L, based on the total formulation. No sublethal effects were observed at this level. Since this concentration is 10x the Maximum Environmental Concentration measured following aerial application at the manufacturer's recommended use-rates (Newton *et al*. 1984), this study indicates that chronic exposure to concentrations of ROUNDUP of up to 10x the maximum concentrations encountered in the environment immediately following aerial application at the manufacturer's recommended use-rates will not affect subsequent seawater adaptation and survival of coho salmon.

## ACKNOWLEDGEMENTS

This work was conducted under contract to Monsanto Co., St. Louis, Missouri, and I expressly thank Monsanto for permission to publish this information. I gratefully acknowledge Dave Mitchell (E.V.S. Consultants) and Tim Long (Monsanto) for their assistance in the studies which form the basis of this paper.

## LITERATURE CITED

APHA. 1985. Standard Methods for the Examination of Water and Wastewater. 16th ed. APHA/AWWA/WPCF. Washington, D.C. 1134 p.

Clarke, W.C. 1982. Evaluation of the seawater challenge test as an index of marine survival. Aquaculture 28:177-183.

Folmar, L.C., H.O. Sanders and A.M. Julin. 1979. Toxicity of the herbicide glyphosate and several of its formulations to fish and aquatic invertebrates. Arch. Environ. Contam. Toxicol. 8:269-278.

Hildebrand, L.D., D.S. Sullivan and T.P. Sullivan. 1982. Experimental studies of rainbow trout populations exposed to field applications of Roundup herbicide. Arch. Environm. Contam. Toxicol. 11:93-98.

Miller, R.G. 1966. Simultaneous Statistical Inference. McGraw-Hill Book Co., New York, NY.

Mitchell, D.G, P.M. Chapman and T.J. Long. 1987a. Acute toxicity of the glyphosate herbicides Roundup and Rodeo to rainbow trout, chinook and coho salmon. Bull. Environ. Contam. Toxicol. 39:1028-1035.

Mitchell, D.G., P.M. Chapman and T.J. Long. 1987b. Seawater challenge testing of coho salmon smolts following Roundup herbicides exposure. Environm. Toxicol. Chem. 6:875-878.

Newton, M., K.M. Howard, B.R. Kelpsas, R. Danhaus, C.N. Lottman and S. Dubelman. 1984. Fate of glyphosate in an Oregon forest ecosystem. J. Agric. Food Chem. 32:1144-1151.

Wedemeyer, G.A., R.L. Saunders and W.C. Clarke. 1980. Environmental factors affecting smoltification and early marine survival of anadromous salmonids. Mar. Fish. Rev. 42:1-14.

# CHANGES IN THE INVERTEBRATE POPULATIONS OF THE MAIN STREAM AND BACK CHANNELS OF CARNATION CREEK, BRITISH COLUMBIA FOLLOWING SPRAYING WITH THE HERBICIDE ROUNDUP (glyphosate).

J. C. Scrivener and S. Carruthers

Department of Fisheries and Oceans
Biological Sciences Branch
Pacific Biological Station
Nanaimo, British Columbia V9R 5K6

## ABSTRACT

Populations of macroinvertebrates were monitored at two sites in the main stream and at sites with bare mud and mud with rooted vegetation substrates in four tributary swamps. Three tributary swamps (750-trib, 1500-trib, 1600-trib) and one site in the main stream were influenced by the herbicide ROUNDUP (glyphosate) after aerial application. Any impacts from the herbicide were not easily detectable because macroinvertebrate densities varied with substrate types, with the seasons and with previous hydrological conditions. In the main stream, a negative relationship between density and stream flow indicated that after frequent freshets macroinvertebrate densities were 42% lower at the treated versus untreated site, although the difference was not statistically significant ($p=0.09$). In the swamps, density of organisms on the surface of the substrate was related to stream flow with a cubic polynomial ($R^2 = 0.45$). Density maxima occurred during median flows, while density minima occurred during periods with extremes of flow. During periods of freshet, densities in the treated swamp were half those of the untreated swamp.

## INTRODUCTION AND METHODS

This paper describes changes in the populations of benthic invertebrates at two sites in the main stream and in four tributary swamps between 1983 and 1986. Three of these tributary swamps (trib.750; trib.1500; trib.1600) and most of their drainage basins were sprayed with ROUNDUP (glyphosate) during September 6-15, 1984 (Reynolds et al. 1989). A treatment of 2.12 kg/ha was applied with a Bell-47 helicopter and 7.9m long MICROFOIL BOOM. In the main stream one site was above (2350m) and one site was below (630m) the confluences with these treated tributaries. Tributary 2600 was an untreated control. The areas that were adjacent to all sites had been logged and the logging slash burned between January 1976 and September 1981. Details of the design and forestry plan of the Carnation Creek Watershed Project were reported earlier (Dryburgh 1982; Scrivener 1988).

Between November 1982 and June 1986, paired samples were collected from two main stream riffles monthly during the summer and every 2 months during the winter. A cylinder (0.144 $m^2$) with a surrounding 200 $\mu m$ mesh net was pushed into the streambed and the enclosed substrate was agitated to a depth of 15 cm. All dislodged invertebrates and detritus were washed by the current into a net that formed the downstream end of the cylinder. The samples were preserved in 5% formalin. In the laboratory, the samples were split with a plankton splitter and a proportion sorted under 50x magnification. Benthic invertebrates were identified to species when possible and the density of mayflies, stoneflies, dipteran larvae, and caddisflies (fish-food organisms) were expressed in no./$m^2$.

At 2-month intervals between May 1984 and June 1986, two or three replicate samples of macroinvertebrates were also collected in the swamps from sites with substrates of bare-mud and of mud and rooted vegetation. A 10 x 10-cm sled was rapidly pulled a measured distance over the bottom and the organisms on the surface of the substrate and grassy vegetation were caught in the trailing 200 μm net (Sibert et al. 1977). Comparable samples were also obtained from tributaries 750 and 1500 on May 11 and September 6 of 1984. No samples were obtained when the sites were dry between July and October 1985. Swamp and main stream samples were processed in the same manner. This sampling technique does not provide accurate estimates of total macroinvertebrate densities in the swamps (Edmondson and Winberg 1971), but it does provide comparable data of the component that is useful as salmonid food (Sibert et al. 1977). Occasionally organisms that lived in the mud were caught when the sled dug into the substrate. These animals were excluded from the analysis (eg. bivalves, nematodes, worms).

Water levels were continuously recorded at B-weir and C-weir. Stage/discharge curves that were updated at least five times a year were used to compute stream flow (cubic feet/sec., cfs) from water level. Mean stream flow during the 60-day period prior to each sampling of macroinvertebrates was used as an indicator of previous hydrological conditions. Flows at B-weir were used for main stream samples, while C-weir flows were used for swamp samples. Tributary C separates the watersheds of tributary 1600 and 2600.

## RESULTS AND DISCUSSION

### Differences in Density Among the Sites

Macroinvertebrates in the main stream and tributary swamps consisted of different communities of organisms. In the main stream, most organisms were adapted to living in fast flowing riffles. Mayflies, stoneflies and dipteran larvae dominated the community (Culp and Davies 1983). Mayflies such as *Cinygmula* sp. and *Epeorus* sp. that have flattened body forms were most common, but *Baetis* sp. was also present in large numbers. Species of *Alloperla*, *Capnia*, *Kathroperla*, and *Nemoura* were the most common stoneflies. Dipterans were mainly represented by midges (chironomids) of the Tanypodinae and Orthocladiinae subfamilies. In the swamps, the fish-food organisms consisted mainly of dipteran larvae, copepods, ostracods, mayflies, amphipods, and caddisflies. Stoneflies were occasionally represented by *Paraleuctra* sp. Mayflies such as *Ameletus* sp. and *Paraleptophlebia* sp. were found at sites with rooted vegetation. Dipteran larvae were represented by midges, biting-midges (Ceratopogonids, no-see-ums), and black flies (Simulids).

In tributary swamps, greater numbers of fish-food organisms were found at sites with rooted vegetation than at sites with bare-mud substrates (Table 1). At rooted sites, mean densities were 4 times greater in tributary 750, while they were 10 times greater in tributary 1500. Therefore data from sites with different substrates were analyzed separately so that any impacts from the herbicide could be detected.

### Seasonal Variation

Seasonal variation of densities made interpretation of herbicide impacts difficult. In the main stream, the density of the benthos changed from 7-fold to 14-fold annually between November 1982 and June 1986 (Fig. 1). An annual peak occurred each summer when water levels were near the minimum, but when surface water still flowed in the stream (Fig. 1). Annual minima occurred when winter freshets were frequent. The minimum density was observed on January 15, 1984 ($375/m^2$; Fig. 1), 10 days after the largest freshet occurred during the study ($64\ m^3/s$; Scrivener 1988).

Table 1. Mean densities observed in samples of fish-food organisms from tributaries 750, 1500, 1600, and 2600 between May 1984 and April 1986. Densities where Scirpus grasses predominated are shown, but they were also included within the rooted-vegetation type.

| Site | Substrate type | Number of samples | Mean density no/$m^2$ | Comparisons by Mann-Whitney U tests |
|---|---|---|---|---|
| trib. 750 | bare-mud | 2 | 50.0 | U = 1<br>p = 0.056 |
| | rooted-vegetation | 7 | 202.0 | |
| trib. 1500 | bare-mud | 2 | 45.0 | U = 0<br>$p < 0.05$ |
| | rooted-vegetation | 5 | 484.9 | |
| trib. 1600 | bare-mud | 20 | 80.6 | U = 33<br>$p < 0.001$ |
| | rooted-vegetation | 24 | 540.6 | |
| | scirpus | 13 | 732.1 | U = 106<br>p = 0.45 |
| trib. 2600 | bare-mud | 19 | 249.5 | U = 96<br>p = 0.002 |
| | rooted-vegetation | 28 | 687.0 | |
| | scirpus | 15 | [illegible] | U = 103<br>p = 0.037 |

Changes of water level in the ephemeral tributaries have forced swamp macroinvertebrates to develop life cycles with a different seasonal pattern. Peak densities occurred during spring, when water levels were moderate and prior to the emergence of adults from the swamps (Fig. 2). Annual lows occurred during summer and autumn, when the swamps were either dry or nearly dry and when macroinvertebrates often entered resting stages (eggs, pupae; Williams and Hynes 1976).

Densities usually varied from $100/m^2$ to $2400/m^2$ annually. This 24-fold change also made any herbicide impacts difficult to detect. The magnitude of annual variation was similar at sites with substrates of bare-mud, but the densities were lower (Fig. 3).

## Stream Flow Influences on Density

In the main stream, the density of benthic fish-food organisms was negatively correlated with mean stream flow during the 60-day period prior to sampling (Fig. 4). Relationships were also obtained between density of macroinvertebrates and stream flow during shorter and longer time periods, but this 60-day mean produced the most consistent results. Stream flow explained 47% of the variability at 630m ($r^2$ ) and 29% of the variability at 2350m in these densities (Fig. 4). Densities were low after frequent fresheting, while they were high during periods of stable low flows. Deviations from the correlations tended to be positive during the spring sampling period just prior to emergence of adults from the stream (Fig.4, triangles). During the summer, very high

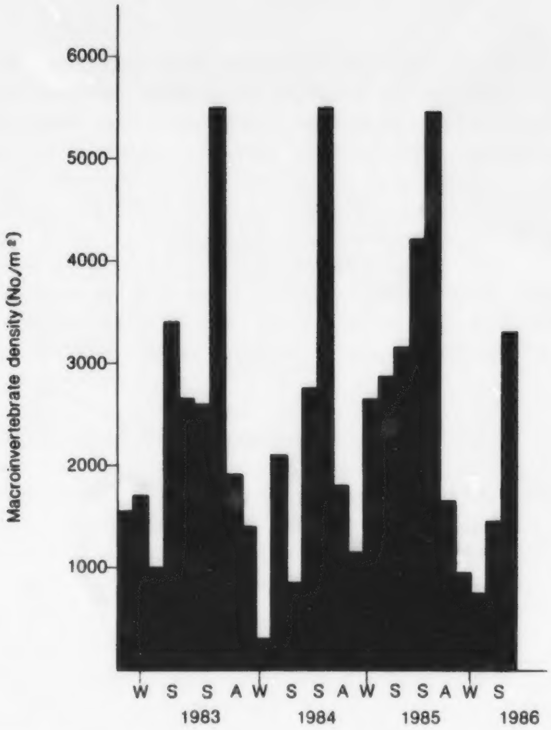


Figure 1. Mean densities of macroinvertebrates obtained for paired samples from station 2350 between November 1982 and June 1986 (winter=W, spring=S, summer=S, autumn=A). This site is 2350m upstream of the estuary in the main stream of Carnation Creek, British Columbia.

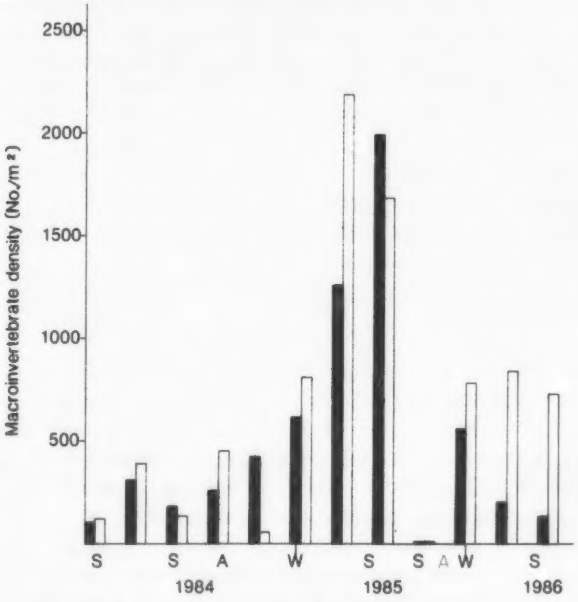


Figure 2. Mean densities of fish-food organisms observed on mud substrates with rooted vegetation in two tributary swamps during the 12 sampling periods between May 1984 and June 1986 (spring=S, summer=S, autumn=A, winter=W). Tributary 1600 (solid-bars) was sprayed with herbicide, while tributary 2600 (clear-bars) was not treated.

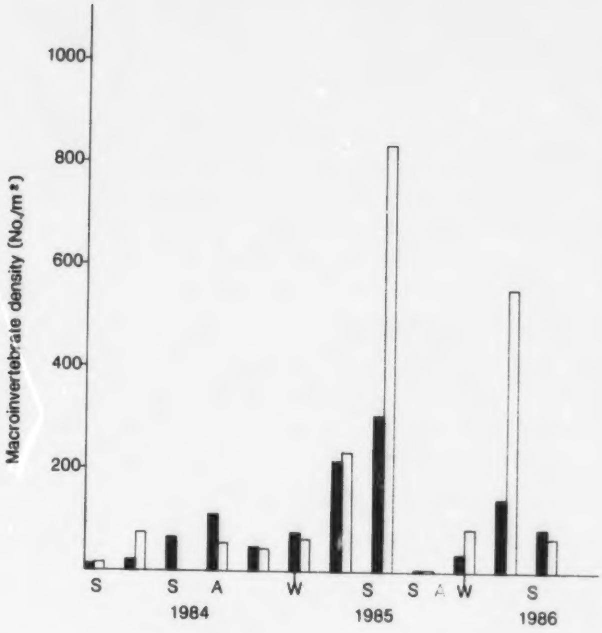


Figure 3. Mean densities of fish-food organisms that were collected from bare-mud substrate in tributary swamps 1600 (solid-bars; sprayed) and 2600 (clear-bars; not treated).

densities probably occurred because the organisms were forced into a smaller wetted area as stream flow declined, and because new recruits from hatching eggs were becoming big enough to be retained by the net of the sampler. During the winter, they dispersed into a greater wetted area and many organisms were scoured from the streambed and transported downstream during freshets (Culp and Davies 1983).

In the tributary swamps density of fish-food organisms was related to stream flow, but the relationship was of a different manner. Unlike the main stream, densities that were obtained with the benthic sled were not linearly correlated with stream flows at either tributary 1600 ($r=-0.08$) or tributary 2600 ($r=-0.04$). When the data were grouped into periods with different ranges of stream flow (0-1cfs, 1-2cfs, 2-3cfs, 3-4cfs, 4-6cfs, and >6cfs) mean densities were significantly different among periods at both tributary 1600 ($F=5.3$, $p<0.01$) and tributary 2600 ($F=3.6$, $p<0.05$). High densities occurred during periods with moderate stream flows, while low densities occurred during periods with extremes of flow. A cubic polynomial explained 45% of the density variation in tributary 1600 and 32% of the density variation at 2600 (Fig. 5). Significant improvements of fit were obtained for each step of the polynomial calculation. Most of the aquatic insects appeared to emerge from the swamps as adults before the summer dry period, while other organisms entered resting stages within the substrate mud. Low densities during the winter probably occurred because organisms dispersed or were lost during freshets.

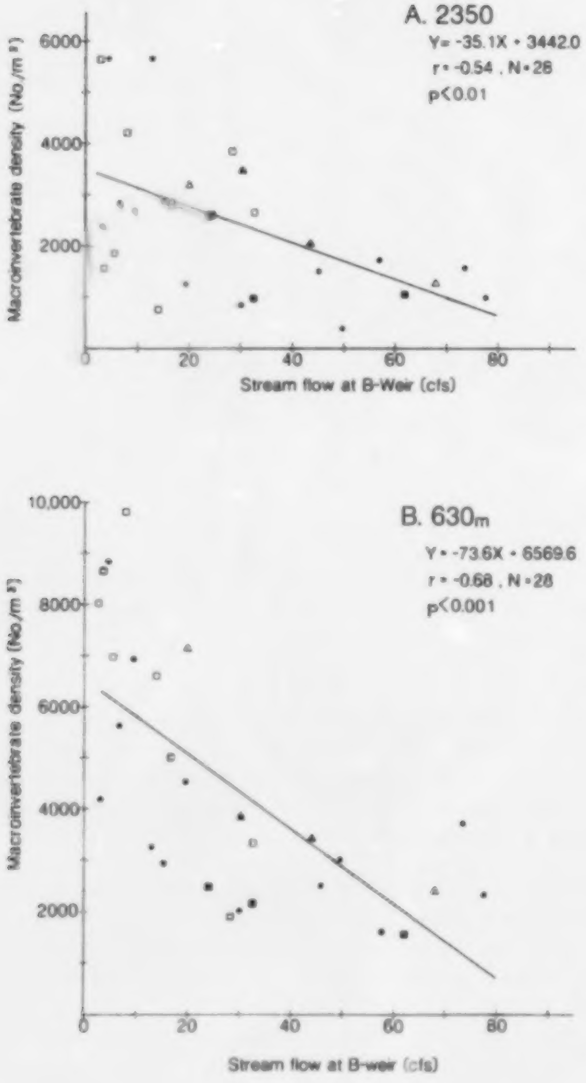


Figure 4. Relationships observed between mean stream flow (previous 60-d period) and the density of benthic organisms in samples from stations 2350m (A.) and 630m (B.) in Carnation Creek. Dots indicate densities from pre-herbicide samples, while squares indicate post-herbicide densities. Solid squares show densities of the first three sampling periods following herbicide application. Triangles indicate densities prior to adult emergence during the spring of 1983, 1984 (solid=pre-herbicide), 1985 and 1986 (open=post-herbicide).

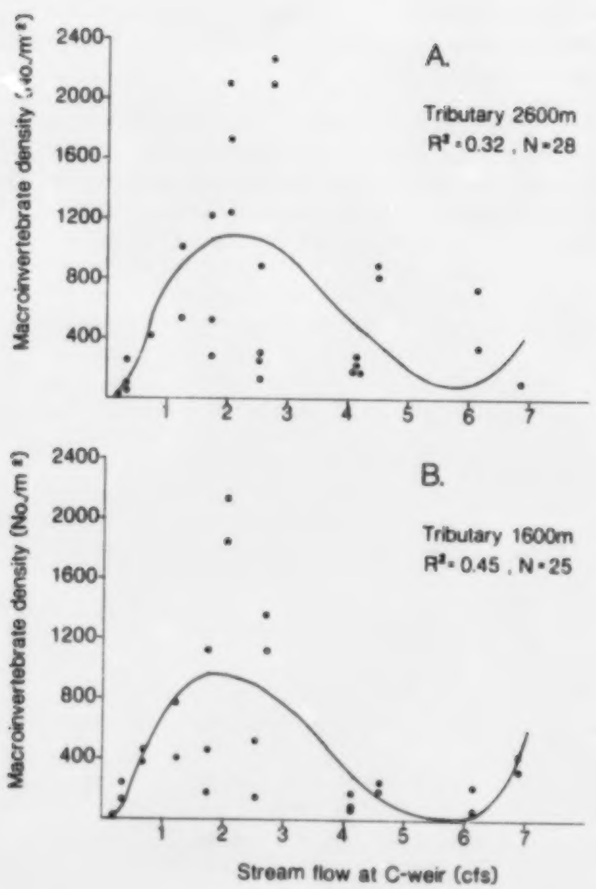


Figure 5. The relationship observed between stream flow at C-weir and the density of fish-food organisms on substrates of mud and rooted vegetation in two tributary swamps at Carnation Creek, British Columbia. The watershed of tributary 2600 (A.) was an untreated control, while 1600 tributary (B.) was sprayed with herbicide.

## Apparent Impacts of the Herbicide

In the main channel, the relationship between density of benthic organisms and stream flow was improved by using the logarithm of stream flow (Table 2), indicating that the relationship is probably not just a simple linear one. Explained variability increased at 630m from 47 to 60%, but it was unchanged at 2350m (30%). No difference was observed between the pre-herbicide and post-herbicide relationships at 2350m, the control site, but there appeared to be a difference at 630m, the treated site, although it was not statistically significant (Table 2; steeper slope, slightly greater intercept). After the herbicide treatment, densities tended to be much smaller at high flows (-54% at 60 cfs), while they tended to be greater at low flows (+30% at 3 cfs). Any negative impact appeared to manifest itself only after freshets of the first post-herbicide winter (Fig.4; solid squares). Probable mechanisms for any loss of organisms were either the compounding influence of the herbicide in the water with scour, or the compounding influence of increased sediment transport with high water velocities during storms. Loss of streamside vegetation can make more sediments available for transport (Bormann and Likens 1979). Sediments that saltate downstream during freshets have increased since logging (Scrivener and Brownlee 1989), and they are known to be an effective scouring agent of benthic organisms (Culp and Davies 1983).

Table 2. Relationships observed between stream flow at B-weir (60-d mean) and the density of benthic fish-food organisms at stations 630 and 2350 before and after the herbicide ROUNDUP was used at Carnation Creek, British Columbia. Stream flow is the independent variable X, while density is dependent variable Y.

| Station and scenarios | Relationship | corr. coef. r | Number sampling periods | Prob. p | Comparison of intercepts |
|---|---|---|---|---|---|
| 2350m | | | | | |
| all yrs | Y = log(X)*-1803.4 + 4499.5 | -0.54 | 28 | <0.01 | |
| pre-herb. | Y = log(X)*-2104.8 + 5072.4 | -0.60 | 15 | 0.02 | F = 0.16 |
| post-herb. | | -0.45 | 13 | 0.12 | p = 0.85 |
| 630m | | | | | |
| all yrs | Y = log(X)*-4259.1 + 9909.8 | -0.78 | 28 | <0.001 | |
| pre-herb. | Y = log(X)*-2963.3 + 7931.1 | -0.70 | 15 | <0.01 | F = 2.65 |
| post-herb. | Y = log(X)*-5610.4 + 11208.5 | -0.86 | 13 | <0.001 | p = 0.09 |

In the tributary swamps densities of fish-food organisms in relation to stream flow were similar for 1600 and 2600 at low flows, but they became progressively greater in tributary 2600 at higher flows. Peak densities were 8% greater in tributary 2600 when flows were 2 cfs (983/m versus 1073/m$^2$), while they became 2-times greater when densities were lower and flows were 4.5 cfs (160 versus 360/m$^2$, Fig. 5). These differences could be entirely due to spatial variation between sites, but this is unlikely because consistent differences between the swamps did not appear until the spring and summer of 1985 (Figs. 2 and 3). Enough samples were not obtained from the swamps before the herbicide treatment (four sampling periods) to compare pre and post treatment times as was done for the main stream. If some of these differences between the swamps represent a real herbicide impact, results would be consistent with those from the main stream. Any impacts seemed to be more pronounced after periods of freshet.

## MANAGEMENT IMPLICATIONS AND CONCLUSIONS

The densities of fish-food organisms vary with the seasons in response to a very dynamic environment. During summer and early autumn, if stream flows are adequate, numbers peak as the next generation enters the larval aquatic stage, as growth and food resources peak (detritus, epiphyton), and when sediments and the bed are stable (Culp and Davies 1983). During the late autumn and winter, numbers decline as organisms disperse or when storm flows with accompanying sediments scour them from the substrate. Numbers also vary with substrate composition and hydrological regime.

Superimposed on these variations were influences from logging and silvicultural activities. Logging impacts were most pronounced during the winter at sites with logging to the stream bank. After logging, benthic organisms were reduced during the winter by 24% at 630m and by 41% at sites with logging to the stream banks (Culp and Davies 1983). The stream banks of all of our sites except 630m were logged. Our results indicated that any herbicide impacts could be similar in magnitude to those obtained after logging, and that they would also be most pronounced after periods of freshet. The organisms were scoured from the bed and transported down stream. They would be lost to the stream ecosystem if adequate habitat could not be reached.

## ACKNOWLEDGEMENTS

Assistance in the field from Messrs. B.C. Andersen, S.G. Baillie, T.G. Brown, A. Langston, and R. Leahy was gratefully accepted. Partial funding for the processing of samples was provided by the B.C. Ministry of Forests. The manuscript was reviewed by H. Mundie, B. Holtby and C. Levings.

## REFERENCES

Culp, J.M. and R.W. Davies. An assessment of the effects of streambank clear-cutting on macroinvertebrate communities in a managed watershed. Can. Tech. Rep. Fish. Aquat. Sci. 1208: 116p.

Bormann, F.H. and G.E. Likens. 1979. Pattern and process in a forested ecosystem. Springer-Verlag, N.Y. 253p.

Dryburgh, J.G. 1982. Carnation Creek logging and silvicultural program, p.36-44. In Hartman, G.F. (ed.) Proceeding of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404p.

Edmondson, W.T. and G.G. Winberg. 1971. A manual on methods for assessment of Secondary Productivity in Fresh Waters. IBP Handbook 17, Blackwell Scientific, Oxford UK. 358p.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. Overview of Carnation Creek herbicide project: historical perspective, experimental protocols and spray operations. This proceedings.

Scrivener, J.C. 1988. The Carnation Creek exerimental watershed project: a description and history from 1970 to 1986, p. 1-10. In Chamberlin, T.W. (ed). Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biological Station, Nanaimo, British Columbia, 239 p.

Scrivener, J.C. and M.J. Brownlee. 1989. Effects of forest harvesting on spawning gravel quality and incubation survival of chum (*Oncorynchus keta*) and coho salmon (*O. kisutch*) in Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. 46(4).

Sibert, J., B.A. Kask and T.J. Brown. 1977. A diver-operated sled for sampling the epibenthos. Can. Fish. Mar. Ser. Tech. Rep. 738: 19p.

Williams, D.D. and H.B.N. Hynes. 1976. The ecology of temporary streams: I. The faunas of two Canadian streams. Int. Revue ges. Hydrobiol. 61: 761-787.

# EFFECTS OF THE HERBICIDE ROUNDUP[1] ON COHO SALMON FINGERLINGS IN AN OVER-SPRAYED TRIBUTARY OF CARNATION CREEK, BRITISH COLUMBIA

L. Blair Holtby and Steven J. Baillie

Biological Sciences Branch
Department of Fisheries and Oceans
Pacific Biological Station
Nanaimo, B.C. V9R 5K6

## ABSTRACT

The responses of coho salmon fingerlings to the over-spraying of a tributary of Carnation Creek with the herbicide ROUNDUP are described. Qualitative observations of caged coho fingerlings at exposed sites in the over-sprayed tributary indicated some stress 2 h after application and within 24 h of application some mortality (2.6%) of those fish was observed. Caged fish at other sites showed no similar signs of stress and no mortality immediately after application. We observed no unusual mortality of the approximately 120 coho fingerlings estimated to be resident in the tributary at the time of the herbicide application. In comparison with unaffected sites, catch per unit effort in the tributary declined immediately after the application but recovered within 3 weeks, suggesting that coho fingerlings had been stressed by some component of the herbicide spray. In comparison with 1-3 years of pre-spray data, in the two years following application no changes in over-winter mortality, growth rates, probabilities of entering and leaving the tributary or timing of spring emigration were observed that could be unambiguously attributed to the herbicide.

## INTRODUCTION

Many studies of the impacts of agricultural and silvicultural chemicals on fish are extrapolations of short-term toxicological effects (e.g. 96-h $LC_{50}$ concentrations), done in the laboratory on standard test organisms under tightly controlled conditions. There are very few studies that examine possible sub-lethal effects that could exist for several years after the application of a toxic chemical. In this study we examine several aspects of the responses of coho salmon (*Oncorhynchus kisutch*) juveniles after a tributary of Carnation Creek used by the fish as winter habitat was intentionally over-sprayed with the herbicide ROUNDUP (glyphosate).

The specific objectives of this study were to: 1) document short-term toxicity of the herbicide formulation on a native salmonid in a natural habitat; 2) document any changes in the way coho salmon exploited the tributary as a winter refuge; and 3) to document long-term (1-2 yr) effects of the herbicide on population parameters of the coho salmon such as mortality and growth rates.

---

[1] Registered trademark, Monsanto Corporation, St. Louis, MO.

## METHODS

Details of the site and the herbicide application are extensively documented elsewhere (Reynolds et al. 1989). The over-sprayed tributary 1600T is largely contained in an 8.9-ha plot that was sprayed in the mid-afternoon of September 14, 1984. Nominal application rate of ROUNDUP was 2.11 kg glyphosate/ha. The application rate achieved was 1.88 kg/ha (Feng et al. 1989). The water temperature ranged between 9.8°-13.1°C. Discharge was approximately 0.01 m$^3$/s at the outlet of the tributary. In most of the middle section of the tributary there was no flow, but rather a series of shallow, isolated pools (Fig. 1). The upper section was mostly dry. The conductivity and pH were not measured but had ranged in the past between 40-60 µmho/cm$^2$, and 5.5-6.5 respectively at similar flow levels.

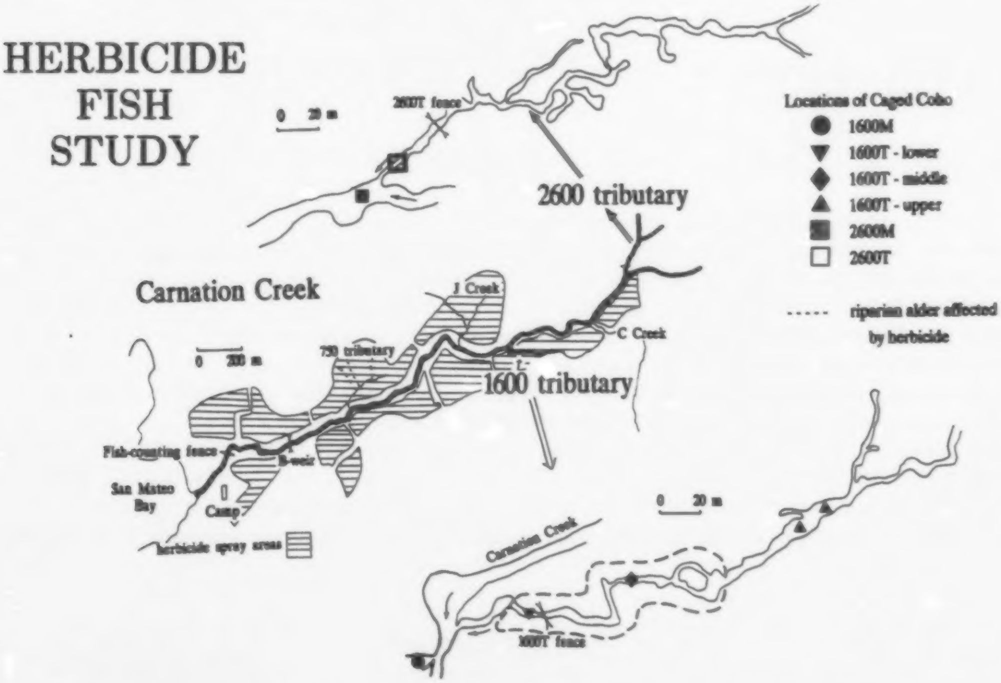

HERBICIDE
FISH
STUDY
0 20 m
2600T fence
2600 tributary
Locations of Caged Coho
● 1600M
▼ 1600T - lower
◆ 1600T - middle
▲ 1600T - upper
■ 2600M
□ 2600T
----- riparian alder affected by herbicide
Carnation Creek
J Creek
C Creek
0 200 m
750 tributary
1600 tributary
Fish-counting fence
B-weir
San Mateo Bay
Camp
herbicide spray areas
0 20 m
Carnation Creek
1600T fence

Figure 1. Sketch map of the study area showing location of fish cages and an indication of canopy over 1600T prior to the herbicide spray.

The riparian vegetation in the lower 200 m of the tributary was dominated by alder 4-6 m tall, which had formed a nearly complete canopy over the stream (Fig. 1). In the middle section of the tributary there were scattered alder and little canopy closure while in the upper sections there was little alder and no canopy. In most of the ecological studies described below comparisons are drawn between the over-sprayed tributary (1600T) and an unsprayed tributary approximately 1 km further up the stream (2600T). Although 2600T is similar in size to 1600T, the riparian vegetation there is less well developed and throughout most of its length there is no canopy and only scattered alders. Winter temperatures in 2600T were generally 1-2°C colder than in 1600T. Both of the tributaries have extensive areas in their upper reaches comprised of ephemeral shallow ponds and channels (Fig. 1). These areas are largely dry in the summer, but are extensively used by coho during winter floods (Brown 1987). Our studies were generally restricted to areas that were permanently wet.

In order to document short-term toxicity, a total of 430 coho fingerlings were placed in 28 mesh cages at six sites in the stream (Fig. 1). Each cage had a volume of approximately 0.2 $m^3$ and was covered on three sides with 3 mesh/cm hardware cloth. Eight of the cages were located in the main-stem below the confluence with the over-sprayed tributary. The fish were caught with a pole seine in a side-channel of the nearby Sarita River and transported to Carnation Creek in twelve 25 L plastic containers. All fish were caught, transported and caged (15-17/cage) within a 2-h period on August 31. One fish died during transportation, probably from injuries sustained during the capture. The remainder of the fish appeared to be vigorous. Several hours after being caged, at which time the fish were first observed as unobtrusively as possible, there were no overt behavioral signs of distress. After a small storm on September 5, all of the cages at 1600M were displaced downstream and lodged in a debris jam causing the death of 16 of the 60 fish and probably severely stressing the remaining fish. The cages were returned to a more protected location. The remaining fish appeared to have recovered by September 14, but the stress of the storm probably compromises using mortality in those cages as an indication of herbicide toxicity. All caged fish were carefully observed every other day until the application date. On September 14 the cages were observed in the morning prior to the spray, within 2 h of the spray, and thereafter in the morning of each day until the fish were removed from the cages on September 21, individually weighed and returned to the Sarita River side-channel.

In order to monitor fish movements into and out of the two tributaries, small, two-way fences at the mouths of 1600T and 2600T were monitored daily throughout the winters of 1981/82 (or 1982/83 at 2600T) through 1985/86. Fish moving into or out of the tributaries were identified and their fork-lengths determined. The numbers entering and leaving a tributary were subsequently used in the estimation of population mortality rates within the tributaries. The number of fish entering each tributary was compared to the the number of coho salmon in the main-stem in order to determine whether the likelihood of a fish entering 1600T was diminished in either 1984/85 or 1985/86. The ratio of the numbers of fish entering/numbers of fish leaving were used to determine if probabilities of emigration from 1600T increased after the herbicide application. In the spring of each year, pre-smolt coho salmon leave the tributaries and eventually enter the ocean as smolts. A relationship between the timing of smolt emigration and spring temperatures has been observed in the main-stem (Holtby 1988a). We examined the timing of emigration from the tributary in order to determine if it had been affected by herbicide-related temperature changes (Holtby 1989).

At various times during the winter we estimated the numbers of coho salmon in the two tributaries using Peterson mark-recapture estimates (Ricker 1975) on fish trapped in small Gee-minnow traps baited with canned sardines. The capture and re-capture runs were always done over-night. The locations of all traps and the numbers of fish caught in each trap were recorded. After the capture run of each estimate, all of the fish were measured to the nearest mm weighed to the nearest 0.05 g, and cold-branded (Everest and Edmundson 1967) with a mark specific for the tributary and particular estimate date. After 1-2 weeks the recapture run was conducted using similar numbers of traps and trap locations. All of the fish captured during these runs were carefully examined for brands and measured to the nearest millimetre.

## RESULTS

The cages in the upper section of the over-sprayed tributary were placed in the middle of a large pool, with no canopy cover (Fig. 1). The tops of those cages were thoroughly soaked with herbicide spray. Two cages were placed in a small pool in the lower part of the tributary that had a dense canopy cover. Very little spray penetrated to the water surface at that point and the tops of the cages were dry. The remaining two cages were placed in the pool immediately below the fence, where the canopy cover was approximately 40%. Some spray reached the water surface and while the tops of the cages were wet, they had not been soaked as thoroughly as in the upper section. Two hours after spraying, the caged fish in the upper section of 1600T showed exaggerated opercular movements at elevated rates compared to fish in the untreated areas. In the opinion of the observers, the fish in that one section were stressed. Fish in other areas, including the lower section of 1600T appeared normal and showed no behavioral changes. All of the fish were behaving normally the next day and remained so until the end of the experiment.

Some mortality occurred in the caged fish in 1600T the day of the spraying (Table 1). Two fish in the upper section of the tributary (3.4%) and one fish at the fence (3.3%) died between Sept. 14, 2 h after spraying and the morning of September 15. No fish had died in 1600T until that time. No fish died at the other sites immediately after spraying (Table 1). If we had completed the experiment on September 20 rather than September 21 then the only deaths that would have been observed would have been in the exposed sites in 1600T. However, on September 21 six fish in one of the four cages in 2600T and one fish in 1600M died (Table 1). While the death at 1600M was possibly the result of injuries sustained in the earlier flood, there is no explanation for the deaths at 2600T. However, the timing of the deaths in 1600T and their occurrence only in the two areas directly exposed to the herbicide does suggest a causal connection with the herbicide application.

Table 1. Summary of short-term toxicity in caged coho fingerlings

| | | | ----- number of fish alive ------ | | | | | % mortality |
|---|---|---|---|---|---|---|---|---|
| site | no. cages | date: | 8/31[a] | 9/12 | 9/14[b] | 9/15 | 9/21 | after spraying |
| main-stem below spray | | | | | | | | |
| 1600M | 4 | | 60 | 33 | 29 | 29 | 28 | 3.4 |
| main-stem above spray | | | | | | | | |
| 2600M | 4 | | 64 | 63 | 63 | 63 | 63 | 0 |
| over-sprayed tributary | | | | | | | | |
| 1600T-fence | 2 | | 30 | 30 | 30 | 29 | 29 | 3.3 |
| 1600T-mid | 2 | | 30 | 28 | 28 | 28 | 28 | 0 |
| 1600T-upper | 4 | | 59 | 59 | 59 | 57 | 57 | 3.4 |
| overall | 8 | | 119 | 117 | 117 | 114 | 114 | 2.6 |
| unsprayed tributary | | | | | | | | |
| 2600T | 4 | | 68 | 68 | 68 | 68 | 62 | 8.8 |

[a] Experiment started.
[b] Herbicide applied mid-day, cages examined before spraying.

We attempted to detect sub-lethal stress by comparing the weights of caged fish among sites using ANOVA with the co-variate of fork-length. We have assumed that the initial distribution of fish was random with respect to fish weight. The fork-length-weight relationship was shown to be the same for all sites. When the fish from 1600M were included, significant between site differences were detected (Table 2). Since the fish from 1600M had been severely stressed by the flood 9 days before the herbicide application, and that stress was clearly shown by their low weights (after standardizing for fork-length), those fish were excluded, and the analysis repeated. There were no significant differences between the standardized weights among the remaining five sites (Table 2). The absence of measurable weight loss is consistent with the observational data from the over-sprayed tributary which suggested that any stressed caused by the herbicide was short-lived.

Table 2. Comparison of weights of caged fish at 6 test sites on termination of the experiment, 1 wk after the spray. "p" values indicate probabilities that the mean weights being compared are not different

| Site | n | mean weight (g) | p |
|---|---|---|---|
| 1600M | 28 | 2.325 | all sites: $p < 0.005$ |
| 1600T-fence | 29 | 2.198 | 1600 & 2600 sites: $p = 0.08$ |
| 1600T-mid | 28 | 2.757 | |
| 1600T-upper | 57 | 2.552 | |
| 1600T-overall | 114 | 2.512 | 1600 overall & 2600 overall: $p > 0.1$ |
| 2600M | 62[a] | 2.650 | |
| 2600T | 62 | 2.355 | |
| 2600 - overall | 124 | 2.502 | |

[a] 1 fish escaped to Carnation Creek prior to measurement.

Another indication of a short-lived stress on the fish in 1600T was the observed decrease in catch per unit effort (CPUE) in 1600T just after the spray (Fig. 2A). One unit of effort was a single Gee minnow trap. Two weeks after the spray, CPUE in 1600T had recovered to pre-spray levels. CPUE in both tributaries was correlated with water temperatures (Fig. 2B), and the observed decline in CPUE over the winter (Fig. 2A) was associated with decreasing water temperatures. The sample point for 1600T immediately after the spray is outside the 1% confidence limits of the temperature-CPUE relationship (Fig. 2B).

There were no significant changes in the abundance of either coho salmon or cutthroat trout (*Salmo gairdneri*) in 1600T when mark-recapture estimates of abundance made 6 days, 2, 4 and 6 weeks after the spray are compared with estimates made 3 weeks before the spray (Table 3). Since there was no measurable mortality resulting from the spraying, the decreased value of CPUE in 1600T after the spraying was probably due to reduced activity of the fish, which might be an indication of stress.

Early winter survival (October-January) was compared in both side-channels for three winters: 1983/84, 1984/85 and 1985/86 (Table 4). The observed survival rates in both 1600T and 2600T are comparable to the overall population survival rates which ranged from 73-92% during this period (Holtby 1988a). The estimated survival rates in the tributaries are similar to those observed in the tributaries before logging (Bustard and Narver 1975). With the exception of cutthroat trout in 2600T, survival rates in the two tributaries were notably constant in the three years. There is nothing to suggest that the survival of coho salmon or cutthroat trout in 1600T was affected by the herbicide, either directly in 1984/85 or indirectly in 1985/86.

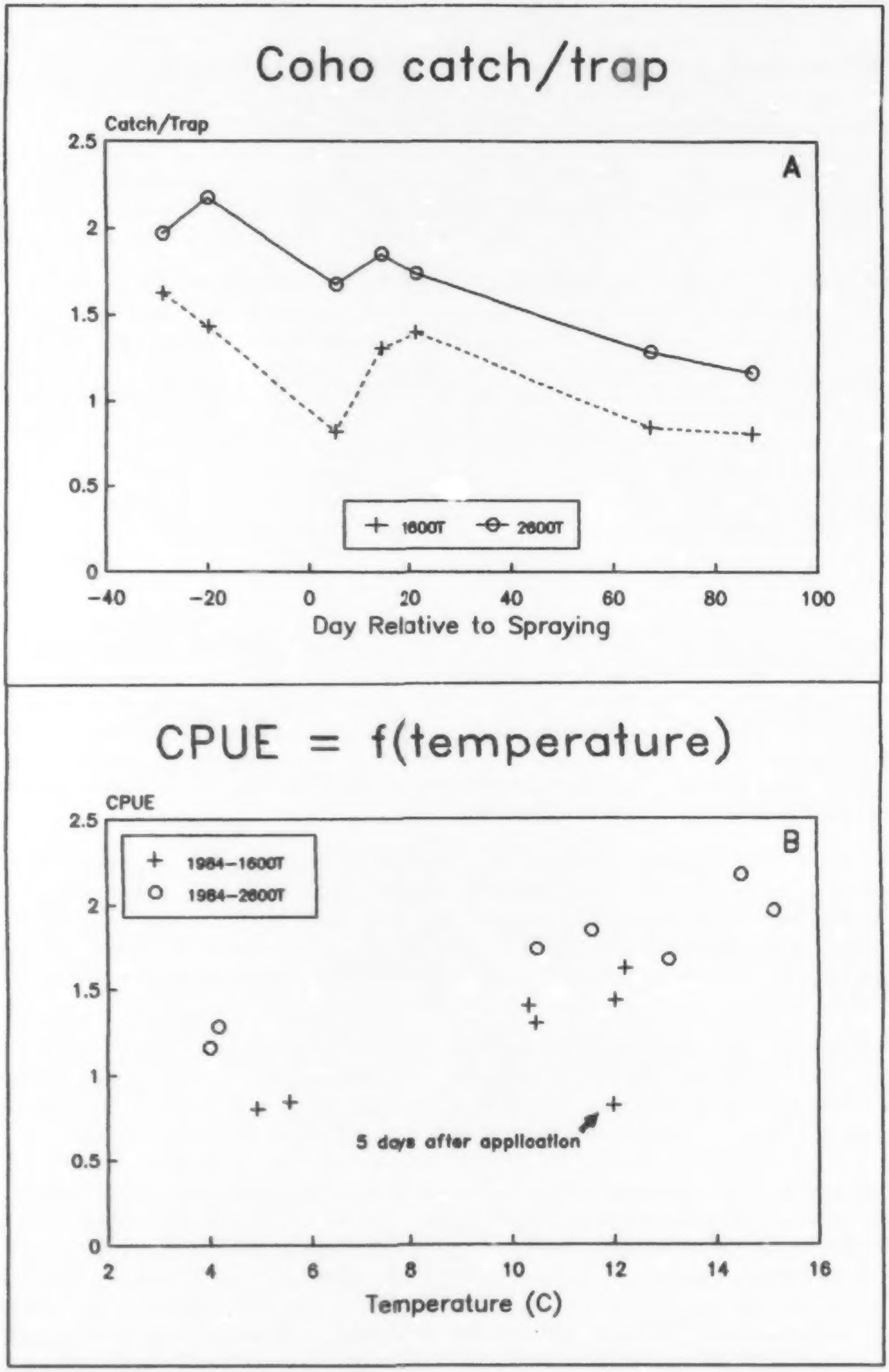


Figure 2. A: Catch per unit effort in 1600T and 2600T for early winter 1984, following herbicide spray in 1600T: B: Relationship btween catch per unit effort and temperature n 1600T and 2600T over the same period.

Table 3. Estimated numbers of coho salmon and cutthroat trout in 1600T and 2600T around the time of herbicide application. The estimated population sizes have been corrected for movements through the fences on each of the tributaries. Approximate 95% confidence intervals are shown for each estimate

| date of estimate<br>days after spray | Aug. 23/25<br>-21 | Sept. 19/20<br>+7 | Sept. 27/28<br>+14 | Oct. 4/5<br>+21 |
|---|---|---|---|---|
| Coho salmon | | | | |
| 1600T | 142 ( 96-227) | 110 ( 76-180) | 156 (101-241) | 116 ( 87-171) |
| 2600T | 176 (125-264) | 232 (160-369) | 201 (149-298) | 185 (129-227) |
| Cutthroat trout | | | | |
| 1600T | 54 ( 31-112) | 59 ( 35-118) | 58 ( 37-120) | 50 ( 27-104) |
| 2600T | 72 ( 45-128) | 119 ( 77-210) | 124 ( 80-212) | 103 ( 74-154) |

Table 4. Over-winter survival of coho salmon and cutthroat trout fingerlings in two permanent tributaries

| | 1600T (treated) | | | 2600T (untreated) | | |
|---|---|---|---|---|---|---|
| year | -population estimate- Sept.-Oct. | Jan. | %survival | -population estimate- Sept.-Oct. | Jan. | %survival |
| coho salmon | | | | | | |
| 83/84 | 353 | 298 | 84.4 | 355 | 303 | 85.4 |
| 84/85 | 118 | 108 | 91.5 | 147 | 118 | 80.3 |
| 85/86 | 324 | 325 | 100.3 | 415 | 323 | 77.8 |
| cutthroat trout | | | | | | |
| 83/84 | 133 | 134 | 100.8 | 89 | 49 | 55.1 |
| 84/85 | 49 | 47 | 95.9 | 103 | 84 | 81.6 |
| 85/86 | 44 | 48 | 109.1 | 134 | 58 | 43.3 |

The growth rate data for coho salmon in the tributaries over the same early winter period gives no indication of any adverse effect of the herbicide in either 1984/85 or 1985/86 (Table 5). In 1600T, growth rates were higher in 1984/85 than growth rates in 1983/84 and 1985/86, but in 2600T the converse was true. However, none of the differences were statistically significant. The higher growth rates in 1600T during 1984/85 could have been associated with the small numbers of fish in that year, but density dependent growth rates during the winter have not been previously observed in Carnation Creek (Holtby 1988b) and no increase in growth in 2600T was seen with similar low numbers of fish in that same year (Table 5). The differences in fish numbers between the years are clearly reflected however, by the differences in size at the start of the winter (Fig. 3). Summer rearing densities have been shown to be strongly correlated with the size of coho fingerlings in the fall (Holtby 1988b).

Table 5. Over-winter growth rates of coho fingerlings in two permanent tributaries. Both instantaneous and arithmetic growth rates were calculated, although arithmetic rates generally fit the data better

| year | 1600T (treated) | 2600T (untreated) | ratio 1600/2600 |
|---|---|---|---|
| arithmetic rates ($mm.day^{-1}$) | | | |
| 83/84 | 0.0497 | 0.0695 | 0.715 |
| 84/85 | 0.0614 | 0.0605 | 1.015 |
| 85/86 | 0.0554 | 0.0693 | 0.799 |
| instantaneous rates | | | |
| 83/84 | 0.000724 | 0.00102 | 0.711 |
| 84/85 | 0.000806 | 0.000815 | 0.989 |
| 85/86 | 0.000827 | 0.000976 | 0.847 |

In addition to simple measurements of mortality and growth in the over-sprayed tributary we considered whether coho salmon were more or less likely to enter the tributary after it had been over-sprayed, and whether fish were more likely to leave it. Five years of fence data were available for 1600T and four years of data for 2600T. For 1600T, coho salmon appear to have been less likely to enter the 1600 tributary in the two winters after spraying compared with the three years before spraying for which we have data (Table 6). The decline in the two post-spraying years was marginally significant at the 10% level ($p=0.09$; two-tailed t-test, adjacent stream section). Although comparisons of 1600T with 2600T are hampered by the lack of data from 2600T for 1981, the numbers of fish entering 2600T in relation to potential immigrants, did not decline in 1984/85 or 1985/86 (Table 6).

Table 6. Numbers of coho salmon fingerlings entering the tributaries during the September-December as proportions (p) of total main-stem populations and numbers in adjacent main-stem reaches

| | 1600T (treated) | | | 2600T (untreated) | | |
|---|---|---|---|---|---|---|
| year | no. in stream | no. entering | p | no. stream | no. entering | p |
| total main-stem population | | | | | | |
| 81 | 6652 | 320 | 0.0481 | 6652 | --- no fence --- | |
| 82 | 7557 | 156 | 0.0206 | 7757 | 96 | 0.0127 |
| 83 | 10170 | 407 | 0.0400 | 10170 | 98 | 0.0096 |
| 84 | 3143 | 49 | 0.0156 | 3143 | 10 | 0.0032 |
| 85 | 6825 | 101 | 0.0148 | 6825 | 359 | 0.0526 |
| adjacent stream reach | | | | | | |
| 81 | 105 | 320 | 3.048 | 70 | --- no fence --- | |
| 82 | 86 | 156 | 1.814 | 133 | 96 | 0.722 |
| 83 | 151 | 407 | 2.695 | 202 | 98 | 0.485 |
| 84 | 32 | 49 | 1.531 | 22 | 10 | 0.455 |
| 85 | 115 | 101 | 0.878 | 47 | 359 | 7.64 |

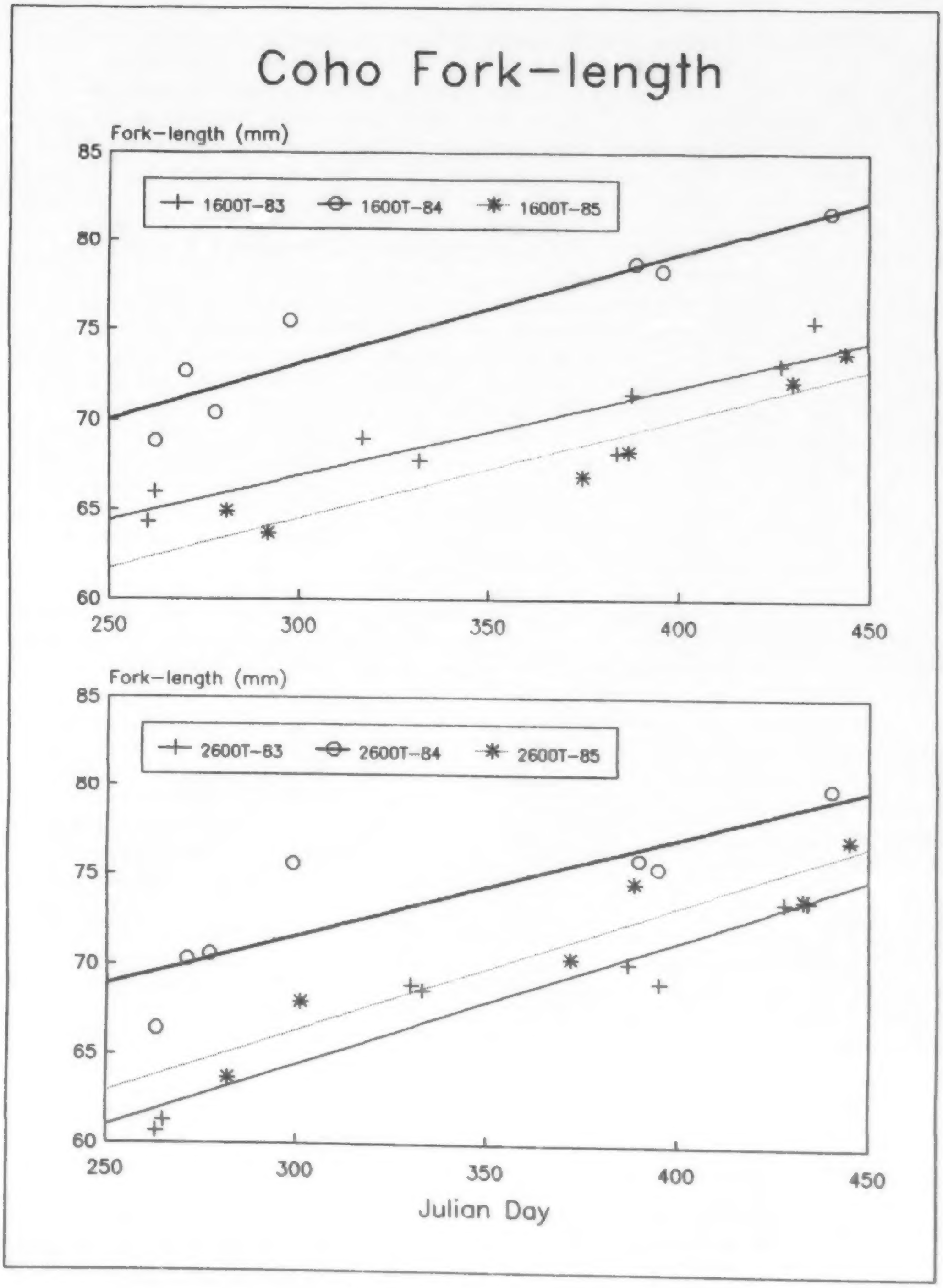


Figure 3. Size of coho salmon in early winter in A) 1600T and B) 2600T.

The number of fish leaving 1600T compared to the number entering the tributary appears to have fallen in the two years after spraying (Table 7). Whether the decreased probability of leaving the tributary was an effect of the herbicide or a continuation of a trend that was in evidence the year before spraying (Table 7) is uncertain, but the changes are statistically significant (p=0.041). However, a similar increase in the probability of remaining in a tributary was observed in 2600T (Table 7).

Table 7. Ratios of numbers of coho entering tributaries to numbers leaving during September-December

| | 1600T (treated) | | | 2600T (untreated) | | |
|---|---|---|---|---|---|---|
| Year | No. in | No. out | No.in/no.out | No. in | No. out | No.in/no.out |
| 81 | 320 | 110 | 2.91 | --- no fence --- | | |
| 82 | 156 | 54 | 2.89 | 96 | 16 | 6.00 |
| 83 | 407 | 60 | 6.78 | 98 | 10 | 9.80 |
| 84 | 49 | 5 | 9.80 | 10 | 0 | - |
| 85 | 101 | 10 | 10.1 | 359 | 2 | 180 |

There was a strong relationship between water temperatures in late spring (February-March) in 1600T and the median emigration date for pre-smolt coho (Fig. 4). Spring temperatures were not significantly affected by the herbicide application however (Holtby 1989), and consequently the herbicide had no indirect effect on the emigration timing of pre-smolts in 1600T.

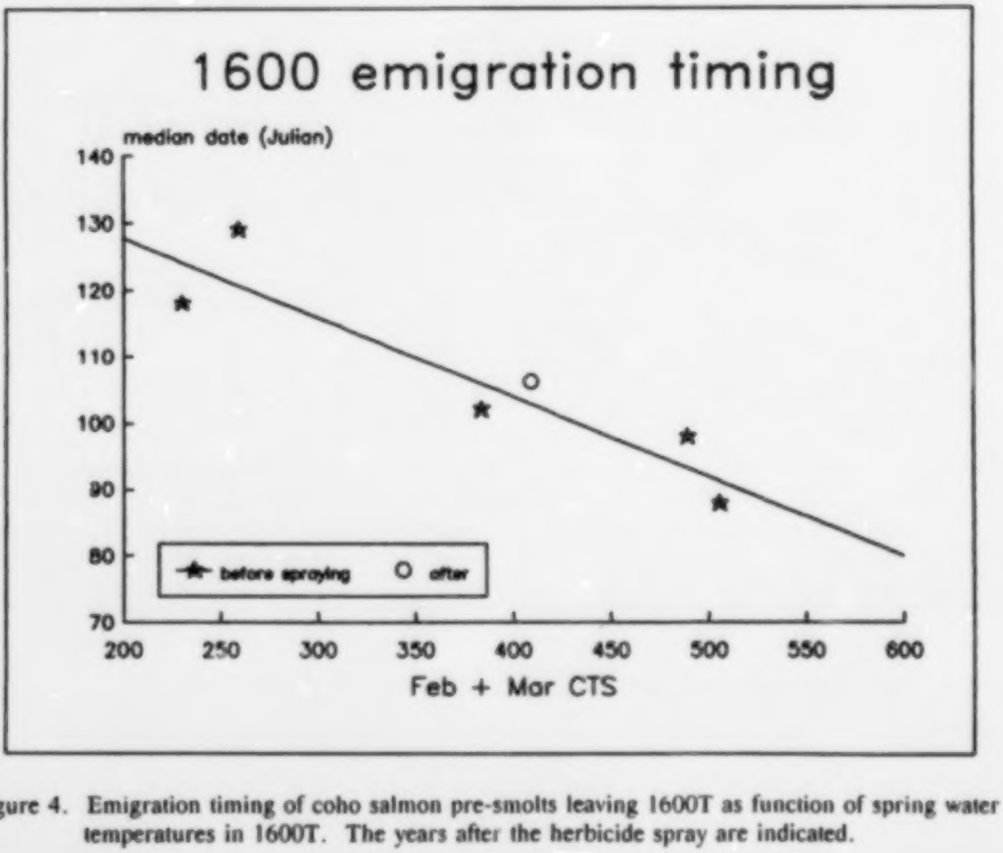


Figure 4. Emigration timing of coho salmon pre-smolts leaving 1600T as function of spring water temperatures in 1600T. The years after the herbicide spray are indicated.

## DISCUSSION

Subjective observations of fish behavior, low levels of mortality after the herbicide application and a temporary depression in the catch per unit effort, suggest that coho salmon in 1600T were stressed by some component of the ROUNDUP glyphosate formulation or by some factor associated with the application itself. The concentrations of glyphosate and its metabolite reported in the water discharged from 1600T for 96 h after the application did not exceed 170 ppb and were less than 40 ppb for most of that time (Feng et al. 1989). Assuming the deposition rate of glyphosate in this experiment was 1.88 kg/ha (Feng et al. 1989) and that, on average water in 1600T was 0.3 m deep, expected maximum concentrations of glyphosate at the outlet would have been 600 ppb, nearly four times those observed. The greatest penetration of the herbicide to the water would have been in the upper half of the tributary where there was little or no canopy. At the time of application, most of the upper half of 1600T was comprised of small, isolated pools less than 0.5 m deep. Measured concentrations of glyphosate near the outlet are probably a poor indicator of concentrations in the upper section. Estimates of the 96-h $LC_{50}$ of ROUNDUP for rainbow trout range from 8.3 ppm (Folmar et al. 1979) to 28 ppm (Servizi et al. 1987), approximately 50-150 times greater than observed concentrations at the outlet of 1600T but possibly as little as 12 times greater than concentrations in isolated pools in the upper tributary. Such levels should not have caused mortality, but might have caused some stress, particularly in the upper tributary where stress was, in fact, observed.

Glyphosate is reported to be rapidly degraded in acidic waters with an abundant microflora (Tooby 1985). Rapid degradation of the chemical and the flushing action accompanying a small storm the day after application dramatically reduced glyphosate levels in 1600T and concentrations were less than 40 ppb 8 h after application, and were near the detection limit (0.05-0.1 ppb) 4 days after application (Feng et al. 1989). Rapid removal of the herbicide, and presumably of associated components of the ROUNDUP formulation, are consistent with our observations of rapid restoration of normal fish behavior (within 1 day), and recovery of CPUE in 1600T within no more than 2 weeks. However, our observation of stress appears anomalous. Hildebrand et al. (1982) observed no stress in caged rainbow trout exposed to ROUNDUP at concentrations approximately 10 times those likely to have been experienced by the fish in our study. Tooby (1985) notes that any deleterious effects of ROUNDUP have been observed at near-lethal concentrations, at least 10 times greater than those experienced in this study.

While there were indications that coho salmon avoided entering 1600T in the two years after the herbicide application, those results were not conclusive. Coho salmon enter their winter refugia during the first fall storms in September-November. It is conceivable that during the first fall storms after the application the levels of some component of the ROUNDUP formulation were detected and avoided by coho. Detectable residues did persist for in 1600T effluent for at least 2 months (Feng et al. 1989). Although avoidance reactions have been seen in the laboratory only at much higher levels (Tooby 1985), those tests were not conducted with fish in their natural habitats at a time when the fish were actively seeking winter refuge.

We were unable to detect any deleterious change in mortality rates or growth rates in the over-sprayed tributary, both in before/after comparisons or in paired comparisons with an untreated tributary. Although there were changes in the abundance of some of the invertebrate food organisms in 1600T (Scrivener and Carruthers 1989; Holtby and Baillie 1989) few of those changes could be ascribed to herbicide effects and any decreases in the abundance of food were either without consequence to the fish or the consequences were too small to be detected. However, coho salmon are highly opportunistic feeders, which makes the task of linking changes in the abundance of potential food organisms and fish growth very difficult.

We suggest that the results we have presented here can be extrapolated elsewhere only with great caution. The herbicide formulation used in this study was not particularly effective in killing alder, which comprised most of the riparian vegetation around 1600T and at least half of the tributary had no or little riparian canopy anyway. The impacts of using a more effective herbicide in situations where more extensive riparian vegetation is present cannot be anticipated from this study. Carnation Creek is in a cool maritime climate where stream temperatures after canopy removal are not a great concern, even during the summer. Removal of the riparian vegetation in warmer situations would produce much larger temperature changes than were observed here (Holtby 1989) and might be damaging to salmonids.

Demonstrating the sub-lethal effects of any habitat alteration of fish is very difficult because of the generally small magnitude of any effect compared to the usually large magnitude of background variation and the dubious use of different sites as controls. Pella and Myren (1974) suggest than 10-20 years of data are minimal requirements to detect 50% changes in numbers of adult salmon. Some components of this study comprised included data from 2 years before spray and 3 years after spraying, a relatively long study in the context of recent ecological research, but probably not long enough to detect subtle and indirect effects of defoliating the riparian zone, or, viewed from a position of advocacy, not long enough to be certain that our failure to detect effects actually means that there were none.

## ACKNOWLEDGEMENTS

Our study was made possible by an operating grant to L.B. Holtby and a contract to S.J. Baillie from the Forest Resource Development Agency, administered through the British Columbia Ministry of Forests and the Canadian Forestry Service. The study was part of the Carnation Creek Experimental Watershed Project, a multidisciplinary forestry-fishery study funded the Canadian Dept. of Fisheries and Oceans, the Canadian Forestry Service, Atmospheric Environment Service and Inland Waters Directorate of Environment Canada, the B. C. Ministry of Forests, the B. C. Ministry of Environment and MacMillan Bloedel Ltd. Thanks to the many individuals who have contributed to the collection of data used in this study.

## LITERATURE CITED

Brown, T. G. 1987. Characterization of salmonid over-wintering habitat within seasonally flooded land on the Carnation Creek flood-plain. B. C. Ministry of Forests and Lands. Land Management Report 44: 42 p.

Bustard, D. R. and D. W. Narver. 1975. Aspects of the winter ecology of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). J. Fish. Res. Board Can. 32: 667-680.

Everest, F. H. and E. H. Edmundson. 1967. Cold branding for field use in marking juvenile salmonids. Prog. Fish Cult. 29: 175-176.

Feng, J. C., D.G. Thompson and P. E. Reynolds. 1989. Fate of glyphosate in a Canadian forest stream ecosystem. This proceedings.

Folmar, L. C., H. O. Sanders and A. M. Julin. 1979. Toxicity of the herbicide glyphosate and several of its formulations to fish and aquatic invertebrates. Arch. Env. Contam. Toxicol. 8: 269-278.

Hildebrand, L. D. , D.S. Sullivan and T. P. Sullivan. 1982. Experimental studies of rainbow trout populations exposed to field applications of Roundup herbicide. Arch. Env. Contam. Toxicol. 11: 93-98.

Holtby, L. B. 1988a. The effects of logging on the coho salmon of Carnation Creek, British Columbia. p 159-174. In T. W. Chamberlin (ed.) Proc. of the Carnation Creek Workshop: Applying 15 years of results. Pacific Biol. Sta., Nanaimo, B. C. V9R 5K6.

Holtby, L. B. 1988b. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (*Oncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 45:502-515.

Holtby, L. B. 1989. Changes in the temperature regime of a tributary of Carnation Creek, British Columbia, over-sprayed with the herbicide Roundup. This proceedings.

Holtby, L. B. and S. J. Baillie. 1989. Litter-fall and detrital decomposition rates in a tributary of Carnation Creek, British Columbia, over-sprayed with the herbicide Roundup. This proceedings.

Pella, J. J. and R. T. Myren. 1974. Caveats concerning evaluation of effects of logging on salmon production in southeastern Alaska from biological information. Northwest Sci. 48: 132-144.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989. Overview of Carnation Creek herbicide project: historical perspective, experimental protocols, spray operations. This proceedings.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. board Can. 191: 382 p.

Scrivener, J. C., and S. Carruthers. 1989. Changes in the invertebrate populations of the main stream and back-channels over-sprayed with herbicide at Carnation Creek, British Columbia. This proceedings.

Servizi, J. A., R. W. Gordon, and D. W. Martens. 1987. Acute toxicity of Garlon 4 and Roundup herbicides to salmon, Daphnia, and trout. Bull. Env. Contam. Toxicol. 39: 15-22.

Tooby, T. E. 1985. Fate and biological consequences of glyphosate in the aquatic environment. p. 206-217. In E. Grossbard and D. Atkinson (ed.) The Herbicide Glyphosate. Butterworth & Co. (Publishers) Ltd. Toronto.

# PERSPECTIVE: RISK MANAGEMENT AND THE PUBLIC

John Henigman

B.C. Ministry of Forests
1450 Government Street
Victoria, British Columbia
V8W 3E7

I am here to help you begin to synthesize the information you have heard over the last two days and begin to get an idea of what it means to you, or what you can do with this information when you go home. Whether you're going to make any changes to your management strategies to make a difference. Or, indeed, can you at all? I am going to offer you about seven perspectives that have come to me in the last couple of days, things that are important to me. I, by the way, am an administrator, so these remarks are things that are important to me. I think they might be important to you. I offer them to you so they may stimulate you to start asking questions both of me and other speakers, and in particular tomorrow. That's important.

The use of herbicides in B.C. forestry is very important in terms of efficiency. I offer to support that in 1987, this year, we put down about 30,000 ha of herbicides. In 1984 we put down 3,000-6,000 ha. You can seen then, in terms of herbicide use in forestry we have made a quantum jump. I don't want to suggest to you, however, that herbicides are a panacea as seen by B.C. Forestry or that they are deemed to be the only method that is appropriate. Control burns and mechanical treatments have increased as well during this period; in fact, in the last while they have doubled in use. On the whole reforestation business, especially backlog reforestation I might add, the heat has been turned up. I was reminded earlier today that British Columbia is the only western province that uses herbicides in any appreciable way in forestry. From a regulatory point of view that might pose an ominous concern. However, it also might be looked at from the point of view that British Columbia is the only province in western Canada that has a substantial forest industry as well, although that may change as Saskatchewan and others come into the market with aspen.

Now, the use of herbicides in terms of regulations is the other side of the coin. It's a very regulated business. The product is regulated in registration; the techniques are a great concern and are regulated very closely both in the permits and in the registration. As well, on the forest site where the stuff is going to be used, opportunity is heavily regulated in the permit process. The management is the subject of fishery and forestry discussions which is a heavily integrated and required process. The training of certified applicators is a very formal process that is fairly onerous and time-consuming and carefully undertaken. Public liaison is part of the process. The resulting data are brought in and integrated into the system that we have now. However, I would suggest that in the short term you are not going to see very many significant changes in the regulatory system in British Columbia that come out of this specific work. You will perhaps, in time. An administrative forester, who knows quite well the state of the silvicultural art in British Columbia, told me that in his opinion the pesticide-free zone and the related buffers that are imposed and used by foresters in their herbicide spraying are not so much to protect fisheries, or potable waters but, as a function of risk management, to keep an angry public at bay. They know very well that if they do what they do now, they can meet their objectives and really that's all they want. I see no data presented here that will significantly change the regulatory registration of products or the provincial regulatory process in the next couple of years. It might in small ways over time, but I think what we've seen is that, albeit some foresters want to reduce the size of their buffers, it's not inside the system by and large. The regulatory permit system will endure.

The herbicide-use program, and by that I mean both its use and its regulation, has evolved over about the last 15 years, and since the royal commission into pesticides and herbicides in the early 1970s has changed, but has endured as a system. It has changed with research added to it, such as you have heard today; it has, in particular, been modified by public discussion, researchers' discussion, by debate--sometimes quite heated--and by legal challenges. All of these things have changed the system, and in my view, have made it tougher and more resilient. The herbicide system, in general, works. It serves the purposes that everybody intended. Fisheries have their resources protected, by and large. It is possible to come up with an exception, but they're rare. Forestry is doing a dramatic job of increasing it's reforestation and the permit system is part of that, and I am sure that the foresters would like it to diminish in bureaucracy, but the system is still allowing them to use herbicides, much more so that other provinces, or say in the western states. The public had direct input; again, you're going to find interest groups that take issue if they don't have enough, but relative to other public interest concerns issues, or areas where the public would be involved, they have a lot of involvement. Wildlife resources also have been looked at more lately, and is being quickly integrated into this regulatory and use process. The system allows the integration of new information such as you have heard and it is very receptive to changes and adaptation in a social evolutionary kind of way. It really does not lend itself at this point to monumental upheaval, e.g., the crossing out of major, basic regulatory requirements or the stopping of the use of herbicides or their use willy-nilly that would otherwise pose a concern to other resources.

So any upheavals, in my opinion, are not in the interest of the province per se. A slow integration of the results is clearly in the interest of the province. It is important that research people continue to explore what glyphosate or other herbicides such as Garlon will possibly do to other resources.

# PERSPECTIVE: THE EFFECTS OF FORESTRY USE OF GLYPHOSATE ON HUMAN HEALTH

David Bowering
B.C. Ministry of Health
3412 Kalum St.
Terrace, B.C.
V8G 4T2

I appreciate this opportunity to spend three days away from my usual work, doing something completely different, and I can accept the fact that a change is as good as a rest. I've heard information about fingerlings and stream flows and I have a visual impression of the map of Carnation Creek. So, I'm going to do my best to return the favour and provide you with a change: I heard somebody say earlier that the bottom line is fish, but I'm not entirely convinced about that, as you'll hear. I am going to try and change things around a bit and ask you to switch momentarily, at least at the beginning, switch brain sides, move over into your right brain, your intuitive synchronistic area.

When I was in general practice, over a period of some ten years, it came as a bit of a surprise to me (probably no surprise to you) that when physicians are examining patients, looking at throats day after day, listening to chests, filling out prescriptions, lab reports and whatnot, their minds sometimes wander. Mine used to wander a little bit, and I found it taking refuge in some alternative ideas, so called. One of the things I found very interesting was traditional Chinese medicine. I never became an acupuncturist and I never really practiced it, but I like to read about it and think about it, as a way of understanding health and disease. So I thought I would just share a wee bit of that with you. Traditional Chinese medicine is based on nature, it's holistic in its approach. It's a different way of thinking about health and disease: you look at the whole person, not just the body. The emotions, the colour preferences, the smells. All these things are important in this sort of diagnosis of what you see before you as a physician. One thing that's important is a person's chosen occupation, where a person may spend their time, the kind of thing they're attracted to in life. So it may not come as a surprise that the people interested in forestry...(Just to step back a minute, the traditional Chinese medicine, at least one major branch of it is involved with the five element theory, where five elements are in harmony with one another. They nourish one another in a circular, harmonious flow.) It may come as no surprise that if I were a traditional Chinese doctor looking at people in forestry I would be interested in the element wood. You people may well have business with the element wood: you may well have imbalances in that area and that would be something I'd think about if I were working with you as a traditional Chinese physician. If you look at wood and some of its qualities, the upside of wood is growth, strength, flexibility.... performing.... I noticed the speaker before me said the process is becoming more flexible and more resilient and these are good qualities of wood. The down side, of course, is "woodness", in other words being "knot-headed", as an example.

You may be interested to know that the organs connected with the element wood are the liver and the gall bladder and the function (this is all very strange to Western thinking)... but the function of the liver and the gall bladder in the system is to make decisions and to sort information. The emotions connected with those organs, with the element wood, are the emotions of anger and frustration; when you can't sort properly and you can't make decisions you get bothered and you get angry. People involved in forestry issues, especially as they relate to health and the public, have probably seen some of that anger, probably felt some of it. Think about it again; stretch your right brain a little bit.

The organ. If I asked you which organ was most likely to be involved in detoxifying and processing the chemicals in herbicides, you would probably guess the liver, correctly. Again, if I was a traditional Chinese public health doctor looking at you people, I would advise you to take very good care of your livers and to be very cautious and careful in the use of things you think might be toxic. From a Western perspective I would offer you the same advice. I'm back into the old cause-and-effect stuff now. I have a slide that shows from the public health point of view, how big an issue forest herbicide toxicity is, related to other things that I'm supposed to be concerned with. I couldn't print it small enough, to tell you the truth. I have no difficulty at all finding hospitals and morgues and death reports filled as a result of other categories: smoking, family violence, alcohol abuse, motor vehicle accidents, obesity, communicable diseases, etc. No difficulty at all. I would have to look very hard, certainly across Canada, to find one hospital bed filled as a result of forestry use of herbicides. There might be one, I'm not sure. Certainly very few deaths. So why am I interested in it at all? The analogy that comes to my mind is that if I am in general practice and someone who is extremely obese, smokes six packages of cigarettes a day, is hypertensive, drinks a twelve pack very night, beats his wife, etc., comes into the office with a hang-nail or a sore toe, there is nothing I can do about it.

I'm forced to deal with the hang-nail. I have to deal with the guy's complaint before we can even begin to make some progress on some of these other issues. The public, in my area of Terrace and the Skeena, sees herbicides in the environment, and in some cases forestry use of herbicides, as a health problem and they complain loudly about it as a health problem and I don't really have any choice but to work through it so we can get on with some of the more important issues. For a minute I want to say a couple of words to get this off the table about ROUNDUP.

I'm an instant expert on ROUNDUP. I got involved in an issue related to some people in Kitimat who had been exposed to ROUNDUP, not in forestry, but around their apartment building, and so I had to very quickly come up with a report for the Kitimat town council as a medical health officer. And so I gathered as quickly as I could what information I could find. What I found was that the acute toxicity, as all of you know, is considered to be very low, that the LD50s for all mammals that have been tested are high. I came to hear that there is something called the Shikamic Acid Pathway in the bio-synthesis of aromatic amines in plants that is a pathway that mammals don't share, and that is presented as the reason why mammalian toxicity is low. There is evidence apparently from rabbits that there is a mild-to-moderate degree of skin and eye irritation associated with exposure to particularly concentrated solutions of ROUNDUP and from inhalation studies in rats they found that the material was slightly toxic. From what I could gather, those animal models seemed to be fairly accurate with respect to acute toxicity if you extrapolate to humans. There hasn't been any really well-documented human exposure information but there is a fair amount of anecdotal material around that tends to support those animal models. There is no good evidence at all, looking at animal models over several generations of any carcinogenicity or mutogenicity and so, when you put all that together, you say "well it's safe isn't it?"

That really takes us to the end of the registration process and out into the marketplace which is where I, as a person involved in community health, find myself. I suspect most of you, once something hits the registration process, feel your real concerns for safety are over. Now, as I say, unfortunately that's where mine have to begin. I'd like to try and understand a little bit why it's so difficult for me to answer the questions that are asked about how safe herbicides really are. You have to look at the fundamentals of epidemiology, the exposures and outcomes. The idea being that people are exposed to something, for instance a herbicide, after which there is a lag time, and there is an outcome and you try to measure both of those things to make assessments. If we are looking at an acute toxic effect, the outcome occurs very quickly and you can often have an easy time putting the two together. If you are looking at birth defects you are looking at a longer lag time, with late mutations often many years, or generations afterwards.

If we are looking at cancer we look at a lag time of ten to thirty years. So you can see obvious difficulties in working from exposure to outcome, particularly if people are concerned about cancer. There are the cohort studies that people occasionally get to do in industrial settings but they are obviously difficult and expensive, lots of opportunity for loss of follow-up. The other kind of study that gets done is a retrospective study where you look at outcomes. If you think you have a theory about what might be caused by something, for instance a particular kind of cancer, you dig up all the cases you find of that type, compare the exposures back in time for people with that outcome and try to decide whether there is a relationship. There is a whole body of epidemiology related to case control study analysis. The bottom is what I label an ideal experiment where you have a homogeneous population of the exact characteristics of the population you want to generalize to. You randomly allocate samples from that population into two groups. You expose one group and give the other group an identical placebo. Nobody knows who's getting what and at the end you unblind the experiment and see if there are significant differences between the exposed and the placebo group.

I noted that even in your--from my point of view--almost laboratory-like setting at Carnation Creek it was often very difficult to come up with something as clear as that. Certainly in the world of real life and exposure to any number of possible substances we can hardly be expected to approach that. Some of the problems then of course are, as I mentioned, the lag time, the so-called natural experiments that we are forced to look at are poorly designed from any sort of scientific point of view, no blinding, no randomization, the exposures aren't measured systematically very often. The outcome variables aren't always obvious and the exposures keep changing as new products replace old. It's interesting, you know, that industry tends to be very sensitive to concern and when red flags go up, often before the real science is in, the product will change because it's not going well in the marketplace and so there is a new exposure.

Now we are back to square one. Certainly glyphosate is a new product and although there is a body of information on acute effects we know nothing really about what happens to human beings who are exposed, especially those exposed over long periods of time.

On the subject of confrontation, again something that I think we are all probably fairly familiar with, I think we have to acknowledge that there is marketing pressure behind a lot of products. I'm fairly familiar with some of the recent research on 2,4-D following the famous, or infamous depending on your point of view, Kansas's Farm Workers Study. There is a tremendous volume of literature produced by a group called the "Industry Task Force" with the Dow people who in a sense countered what they felt was adverse publicity by this one study. And we all know in science that funding has a big part to play in what gets done, although hopefully within that we are able to sort through and look at good research and bad research and make appropriate decisions about it. I've got something I call "environmental fundamentalism," no offense to people who happen to be religiously fundamentalist, I use that word to mean people who see things entirely as either black-and-white and are impossible to reason with in any sort of gray areas. This is the phenomenon of quoting things out of context, taking one small passage from a study and holding it up and saying "look at this, here's a chromatid exchange problem related to pesticides in such and such a study"; but if you look at the thing in context, really there was no conclusion and the study wasn't even looking at what people claim it was.

On this one, as I say, you can't do human experiments because unlike medicines, which most physicians are familiar with, there are no potential benefits that I know of to being exposed to herbicides. When we deal with medicines we can set up experiments like that ideal one I showed you because there are tradeoffs and we believe there is a benefit and we can actually get some pretty good information about drugs. This is a new area for a physician to be involved in; there are no potential benefits so we can't outright do human experiments.

The other day when I asked the question about people being exposed to the overspraying. From my point of view it would have been great if people weren't wearing protective gear and if they would have been willing to be part of an experiment: to submit urine samples. I wouldn't have expected glyphosate in urine, but we could have collected some sort of biological sample that we could analyze and find out what their exposure really was. That would never pass an ethics committee and we might as well forget it; people would probably be wearing six layers of space suits if we even tried to do such an experiment. Post-marketing surveillance is what we call our attempt to find out about exposure, and the information that we can get is like pesticide permits; we can look at them and see where pesticide permits were granted. We can look at sales records for pesticides and herbicides, occasionally special studies are done to find out about exposure. There have been some studies looking at urinary metabolites of people using backpack sprayers or in farm workers.

Outcome reports--occasionally physicians will report that I've got a patient here who got sprayed with something and seems to be sick--that's usually in the area of acute effects. Cancer registries--B.C. is fortunate in having a Cancer Control Agency that does a lot of cancer mapping, incidence mapping, so you can attempt to correlate rates of various things with the exposures that you know about. Birth defect registries--again in B.C. we are kind of unique in having what they call a birth defect monitoring system in place--the vital statistics division of the Ministry of Health has this monitoring system in place. Ideally a red flag goes up when there is a cluster or an unusual rate of birth defects of a particular type in a particular area. Hospital records pesticide incident monitoring system is something that I think they used to have in the U.S. I'm not sure that they still do; it is really just a computer listing of all reports of exposure to pesticides. If there is a health effect involved it's something you can look at to see if there are patterns if you are concerned about a particular herbicide. To my knowledge we don't have anything of that sort in Canada or in B.C.

Some of the issues. From a point of view of someone in public health wanting to find out about exposures and outcomes in terms of herbicides, access to data can be an issue. Much of the registration data, the actual original studies on rats and rabbits, is not readily available to even physicians or public health people or to provincially funded research groups. There is a group that looked at the effects of chemicals in agriculture and forestry--the use of chemicals on reproductive problems in New Brunswick, a three-page report that came out last year. The author then wrote an article in the Canadian Medical Association Journal this summer complaining about that point. That they really had a tough time getting particular information about toxicology, the original research on toxicology, and no offense, but Monsanto was the group they seemed to have the most difficulty with. And they actually got a fair amount of their information through the U.S. Freedom of Information legislation. As I should point out, as I became an instant expert on ROUNDUP, I found everyone that I talked to, from Agriculture Canada to Monsanto, to be most helpful, but what I got were summaries. People had already looked at the data, drawn conclusions and printed it up. The difficulties with post-marketing surveillance has pointed to the fact that "no demonstrated human health effects" doesn't necessarily mean "no effects" and I really can't stress that one too much. It's very difficult to pull off a proper epidemiological study. Just because we haven't been able to show something doesn't mean it may or may not be happening. The recent association that's been made between aspirin, children who have had chicken pox and Rye's syndrome is a good example of that; very common exposure, very rare outcome, plenty of opportunity to look at it, but the interactions are so complex that it has taken a very long time to put that one together. Passive versus active information gathering, who's going to look for this information, who's going to keep these registries of exposures and outcomes? Its risks and benefits, again, something in a sense that we are all involved in: in health if you're gambling there's not much I can tell you about risks, long-term risks in particular, but in your industry there is certainly a lot you can do to reduce exposure. I refer to the regulations that require people to wear the proper gear, and being very site specific and careful in your use of these materials. Also in documenting and demonstrating the benefits to the public at the provincial level and municipal level and throughout the democratic process. The people in these communities, if they are well-informed, will hopefully make good decisions. I won't talk about the process, since that will come out in the workshops, but I see that as a very key area. The process is ongoing: the evolution of how the democratic process works and the role of science and intuition; the bottom line is who decides and how are decisions made.

I've got a good old-fashioned fundamental virtue listed last, which is prudence. There is a degree of uncertainty in terms of long-term toxicity and that's inevitable; there is nothing we can do about that. Public concern, as you know, in some areas and over some issues, is quite high, and I'm suggesting the evaluation of alternatives ought to be encouraged. This is a page from the report that I gave to the Kitimat council. I had two weeks to get this out and there were tremendous feelings flying, lots of headlines, lots of red flags being waved. Just to give you an idea of the ways a person might look at this, I actually did a survey of the people in these townhouses to see if they had in fact experienced symptoms. There was nothing much in the way of objective data, most of the people who complained of symptoms had not gone to physicians and no laboratory tests had been done so there were just some people saying we've got 35 people with all these symptoms as a result of this spraying.

So, I went in and did a survey and asked about symptoms and then I looked at this pesticide incident monitoring system they have in the U.S. I found 30-some reports, mostly sprayers working with chemicals who had been exposed to glyphosate and I just counted up the symptoms that they had reported. None of this is hard data and none of this is very scientific, but was to see if the pattern fitted with what the people in the townhouses experienced. You can see that 58% of the townhouse people complained of headaches following the spraying; the U.S. sprayers were only 15%. Skin rash was pretty much the same and skin rash is something that you might expect given the animal toxicology of ROUNDUP. Nausea or vomiting not all that different really, considering the small numbers. Eye irritation, or inflammation, 41% of the U.S. sprayers experienced that, only 16% of the people from the townhouses, and again eye irritation is something that one would expect from the rabbit testing. Sore throat: pretty much the same. Nose bleeds is an interesting one and the people were making a lot of that. The children had nose bleeds, 19% of the townhouse people reported nose bleeds and it was mostly in the young people. None of the sprayers in the incident monitoring system reported that. That was one particular small area where I would have loved to have gotten hold of the original data to see if rats were getting nose bleeds when the LD50 studies were being done. Obviously, this is sensitive information for the public to handle, to read about the agonizing deaths of various animals as the LD50 levels are approached, but hopefully it can be useful information and there is a place for that within the public health range.

Key words to leave with are Prudence and Humility in terms of acknowledging that there is a lot we don't know. I've certainly heard that although you've learned a lot about glyphosate and how it affected Carnation Creek there are also a lot of areas where you need to know more. The Process--is an extremely important thing to look at. Exposure--it's important to limit exposure because as I say, there are a fair number of things we don't know. I want to admonish you to keep up the good work. I've certainly enjoyed the quality of the presentations. I almost look forward to being involved in forestry issues as the process continues to evolve. I'd like to now quote a well-known politician who has an interest in forestry and therefore by definition has a liver problem and say that if someone will buy me a drink I'll quit now.

## DISCUSSION GROUPS 1 & 2 - SOILS

Group Leaders - Mark Walmsley and Terry Lewis

**Conclusions**

The conclusions from our groups are:

1. Glyphosate and its major metabolite, AMPA, appear not to be subject to significant leaching, primarily due to strong adsorption within the soil complex. These adsorption processes are not well understood.

2. Soil biological activity is affected very little by glyphosate. It seems that applications of the herbicide may result in a short-term variation (up to 1 month) in microflora numbers. While little impact has been observed, we must accept also that studies have only been short-term. There appears to be a need to examine the effects of glyphosate on soil organisms more intensively and over a longer period.

3. Herbicide effects on biogeochemical processes appear minor in comparison to those caused by logging, site preparation or alternative vegetation management activities. This was a point that was driven home numerous times in our working session; we have to look at the use of herbicides as one tool within a broad spectrum of tools, not only from the point of view of vegetation management but also with respect to other forest management activities.

4. Herbicide use is not expected to cause increased soil erosion. The evidence does not indicate a correlation between the use of herbicides, normally, and an increase or acceleration in surface soil erosion of mass movement. However, we should recognize a need to retain what we term 'brushy seral communities' (e.g., red alder) on severely degraded sites that are rehabilitating. We are concerned with marginally stable sites, for example on the Queen Charlotte Islands, or on the west coast of Vancouver Island, and on the mainland. After these sites have been denuded by slides, red alder communities commonly help to rehabilitate them by stabilizing the slope and increasing site productivity.

**Recommendations**

Our recommendations for further research can be summarized in the following five points.

1. Although the results of this study have shown that dissipation rates for glyphosate were quite rapid, it appears to us that further work is needed in understanding not only rates but also the processes involved in dissipation of the herbicide, particularly under varying environmental conditions and in different biogeoclimatic units.

2. We feel that the mechanisms of soil adsorption and desorption of glyphosate in relation to soil phosphate are poorly understood and require further research. In this study, a good adsorption relationship with organic matter has been shown, but there is evidence also for quite a range of adsorption sites in soils, including clay, minerals and sesquioxides, which may also play a role in herbicide efficacy and dissipation dynamics. Organic matter is obviously very important but perhaps the different fractions of organic matter are involved in different ways.

3. We discussed evidence from other research that there appears to be a small proportion of glyphosate (about 5%) that is quite slow to degrade. Factors and mechanisms that affect the degradation of this 5%-fraction need to be determined. There may be a linkage between this particular fraction and some of the adsorption mechanisms mentioned in Point 2. Perhaps this small fraction is so strongly adsorbed on the clay or organic matter present that it is protected from microbial degradation.

4. We would like to see an evaluation (using Kimmins' approach, perhaps) of biogeochemical changes resulting from vegetation removal alone. The study should test some manual cutting treatment versus the use of herbicide to isolate the effects of the herbicide per se from vegetation removal or cover reduction itself. We felt that these two effects are confounded in existing study results and information.

5. A relatively straightforward laboratory study is needed to look at the effects of temperature and soil type differences on the microbial degradation rates of glyphosate. This study is essential if we wish to understand the processes involved in herbicide dissipation.

## DISCUSSION GROUP #3 - WATER: HERBICIDE CHARACTERISTICS AND WATER QUALITY

Group Leader - Doug Wilson

### Conclusions

The results of the Carnation Creek Study, as well as other work that has been done in B.C. and in Oregon, basically show that herbicide residues are transient in streams. Glyphosate does appear to persist in sediment, but there is some feeling that these residues in sediment are not bio-available. The mobility of glyphosate in the streams studied can be related to major rain storm events. The in-stream herbicide levels that have resulted from operational sprays in the Carnation Creek study were not observed to be acutely toxic to fish. Also, our current knowledge and the evidence we have seen from some of the sublethal effects research, albeit laboratory research, indicate that subacute effects are unlikely.

We indulged in some discussion with regard to public perceptions of the use of herbicides around streams. The public concerns, as you may be aware, remain high. There is a concern about the proximity of herbicide treatments to public water supplies. One of the most intractable problems is the public concern for possible long-term effects of low level applications of herbicide on the environment. We agreed that public perceptions of risks are dramatically different from those of the users of herbicides. The public perception of risk appears to arise because they do not feel in control of the use of herbicides in forestry and on public lands; they do not really know what is going on in forest management; and they feel threatened by this situation. We contrasted this to, for example, cigarette smoking or drinking alcohol where people feel that they are in control but they do not perceive these activities as greater risks.

**Recommendations**

1. We agreed that it would be very useful to consolidate the environmental and forestry information and make it understandable to the general public. An example of this could be the translation of the results generated by the Carnation Creek study into layman's language.

2. There has to be more of a 'show-and-tell' effort to inform the public about the use of herbicides in forestry. The B.C. Forest Service has been doing some of this by showing their operations and the results to farmers in local areas who are interested in what forest management activities were underway in the watershed of concern.

3. Further research:
   - (a) Because the surfactant used in ROUNDUP is more acutely toxic than the glyphosate itself, it was felt that further research is needed to generate useful data about the toxicity and environmental fate of the surfactant.
   - (b) We are concerned about ephemeral streams as potential sources of herbicides to mainstem streams. Research is needed on the movement of herbicides from ephemeral to mainstem streams.
   - (c) Another research need is information on the toxicity and environmental fate of AMPA.
   - (d) More research studies are needed on the 'worst case' scenarios, and toxicity and environmental fate for other chemicals (e.g., Garlon).

4. To reiterate, we feel it would be very useful to have a consolidation of summary statements, conclusions and recommendations from the Carnation Creek herbicide project.

## PESTICIDE-FREE ZONES/BUFFER ZONES

**Conclusions**

After a discussion of the pesticide free zone (PFZ) and buffer zone (BZ) concepts, we concluded that the PFZ generally protects both water/stream quality and the riparian vegetation/habitat. The consensus of our discussion group was that the PFZ was most important for the protection of the riparian zone.

There was some discussion of the use of the MICROFOIL BOOM along streams; we felt that the recommendation for using a 10 meter PFZ and a 25 meter BZ was acceptable. We felt that this recommendation would be useful in B.C., particularly given the accuracy and precision of the microfoil technology. We would like to see some analysis of the economics of ground treatment versus the use of the MICROFOIL BOOM in sensitive areas; it might actually be more cost-effective to use the MICROFOIL rather than ground treatment in areas where aerial sprays using conventional equipment cannot be used.

As I mentioned earlier, we concluded that the PFZ is primarily for the protection of the riparian zones. There was some discussion about possible impacts of the new coast fish/forestry guidelines. There was much discussion about the PFZ and BZ evolving into streamside vegetation management zones, based on stream classification. We feel that the PFZ and BZ are good concepts; they certainly have widespread public acceptance, and should be maintained for the next few years while more impact information is collected. Most people in forestry are aware that individual, site-specific treatments, particularly manual treatments can occur within the PFZ and BZ, so the use of these concepts should be continued.

**Recommendations**

1. We feel that there should be more monitoring in the PFZ and BZ to determine the effectiveness of these zones in buffering possible adverse impacts from operational forestry treatments.

2. There needs to be development of a policy on the use of the PFZ around ephemeral streams, and research is needed on the movements of herbicide from ephemeral to main streams.

3. Research is required to determine the effectiveness of the PFZ and BZ in protecting domestic water quality and supplies, and on the mobility of herbicide residues in watersheds used for domestic water supplies.

## DISCUSSION GROUP #4 - WATER

Group Leader - Dave Wilford

### Hydrology

The major influence on both site and watershed hydrology is the initial forest harvesting. Herbicide use extends the period of effect, but since the application is intended to accelerate the growth of coniferous regeneration, the net effect is seen as positive.

If herbicides are used for rehabilitation of sites with deciduous forests, the net effect will be similar to the original clearcutting.

While it is recognized that small roots are important for the maintenance of slope stability, operational staff have not encountered mass wasting subsequent to herbicide application. The erosional problems encountered were associated with the original logging disturbance. The researchers in our discussion team did not have personal experience with mass wasting subsequent to herbiciding, nor did they know of any literature references.

The use of herbicides to release conifer regeneration was seen as a positive treatment relative to rain-on-snow. Such treatments will speed up the return to pre-harvest conditions.

Site hydrology was seen as an important factor for herbicide mobility, but the level of importance is dependent on the herbicide itself. ROUNDUP quickly binds to soil particles and off-site movement was not seen as a problem. The fact that ROUNDUP binds so easily to soil is evident when one considers how ineffective the herbicide is when the mix-water is dirty.

### Herbicide Characteristics And Water Quality

Rate of siltation and sedimentation were not considered to increase following herbicide applications. Effects on fish habitat were seen as:

- stream temperatures increase - this can be positive or negative depending upon the natural temperature levels. Whether positive or negative, the effect was not seen as a long-term influence.

- riparian litter input - decreases with herbicide application. This is a negative factor but it is a short-term effect. The effect would be significant if a situation developed in which the stream had a closed coniferous canopy.

Herbicides are poisons and they can have a toxic effect on fish. Recognizing this, the team was relatively surprised with the research results indicating that ROUNDUP had a very limited and non-persistent effect on fish and other aquatic life (we were not totally surprised because all of the previously reported research indicated that ROUNDUP was not a serious hazard to the environment). Even doing the tests with the commercial chemical, the surfactant and degradation products likewise had very limited effects. Increases in nutrient flow were not reported to be problematic. These results improved the confidence of operational staff in the use of the herbicide - it is not an environmental disaster.

The current studies into sublethal effects on fish were endorsed. This work may not lead to a relaxation of PFZ regulations along main fish streams, but it may provide useful data for the development of guidelines for the overspraying of tributary streams.

## Domestic Water Quality

As noted above, herbicides should not alter sediment rates, flow volumes, or the regulations of runoff. The release of nutrients could be a concern in some situations where nutrient levels in streams are already high.

The group recommends that acceptable and safe levels of herbicides be defined for potable water use. While domestic water users do not want any herbicide in their water, if acceptable levels were established, field staff could have a better level of confidence. To date, the water quality monitoring projects in domestic watersheds have not reported any ROUNDUP. This indicates that the applicators are making efforts to use the herbicide carefully.

When herbicides are used in domestic watersheds, it is important to know what the water is used for (i.e., drinking, irrigation, etc.). This knowledge was seen as critical for the applicator to take precautions and proceed with confidence. Of note, a forester in the group indicated that, when he encountered an area with numerous small watercourses draining into salmon-rearing corrals, he would use only hack-and-squirt, not aerial methods of application. The use of herbicides in domestic watersheds relies on a knowledgeable public. R & D were seen as major factors if herbicide projects are to be supported (or even allowed).

## Buffer And Pesticide-Free Zones

It is surprising that while the results of the Carnation Creek Herbicide Project showed limited impacts, even in over-spray situations, **all** of this discussion team supported the continued use of the PFZ. PFZ's are taken as a given for fish-bearing streams. We did see a need, though, for research or extension to define situations where tributary streams could be over-sprayed. We see a need for a stream classification system that could be used to identify these situations. Our enthusiasm was held in check by a recognition that herbicides are "deleterious" and that, by law, it may not be possible to over-rule the PFZ. We noted that herbicides (particularly ROUNDUP) tend to dissipate and breakdown rather than accumulate in the food chain (such as DDT does). This fact should assist in helping to reduce the need for PFZ's on small tributary streams. If PFZ's are relaxed, we saw a need for R & D to improve the knowledge and judgment of applicators. They would have to have a crystal-clear understanding of where and where not to over-spray.

Both PFZ and BZ have an effect on silvicultural objectives and cost. The effect is least in the case of ground application, but can be significant with aerial application. Our group noted that in some cases the objectives can change significantly, as in cases where it is decided to reclassify deciduous species as commercial. The use of preharvest silviculture assessments (PHSA's) was seen as a very positive move. They lay out the whole forestry process and allow for a thorough referral review and input to plans. Options can be discussed and such factors as roads and block layout can be determined based on what is seen as acceptable. This discussion of options should include the environmental effects of alternative site preparation techniques (some can have greater adverse impacts than herbicides). PHSA's should help solve some of the referral problems associated with treatments of older logging sites.

Both physical and biologic site factors have an influence on buffer strip recommendations. Unfortunately, these factors are not taught in the current courses: they are learned operationally (through referrals and participation in operational spraying projects).

## Other Points

Silvicultural treatments such as prescribed burning, mechanical site preparation, and herbicides all have potential risks and environmental impacts. Herbicides can produce the least impact in some situations. This should be recognized at the PHSA stage. An interesting risk associated with herbicides was not discussed in the main workshop, and that has to do with the shift in plant species and a subsequent increase in the fire hazard. One group member related a situation from this summer in which a herbicide-treated area was burned. The area had changed from a shrub community to a grass/forb community. Due to the very dry summer, the new community dried and cured early in August (earlier than the shrub community would have). Interestingly, the fire was started by a careless worker who was manually cutting brush in an adjacent area.

There was quite a discussion in the main workshop about ***real world*** research. Our group concluded that the Carnation Creek Herbicide Project was not a ***real world*** situation due to the equipment used, the time of spraying, and the amount of water mixed with the herbicide. We wondered if the results would have been significantly different if the project had been operational. We recognized that efficacy would have been higher and stream temperatures would have been increased higher than those recorded. What other impacts would have been found? There is a need for real ***real world*** research.

In the main workshop we concluded that the operational application rate of ROUNDUP resulted in a concentration below the $LC_{50}$ level. We also saw photos of the strip of dead vegetation left by an aerial application of ROUNDUP. Our group wondered how environmentally serious was the herbicide drift beyond the vegetation-kill swath? If the direct application of ROUNDUP to streams had a very minor effect, could we conclude that the herbicide does not need a BZ to protect the PFZ?

## DISCUSSION GROUP #5 - AQUATIC ORGANISMS

Group Leader - Steve Samis

Our discussion began with an overview of the relevant terms, such as the 10 meter pesticide free zone (PFZ) and buffer zone (BZ) concepts. It was then assured that everyone agreed on the principles for discussion. It was established that the 10 m PFZ is a requirement in B.C.; it protects potable water supplies, fisheries waters, riparian areas, and critical wildlife habitat. As John Henigman stated yesterday, the 10 m PFZ is also expected and deemed necessary by the public. A BZ is a recommendation. It is site-specific, flexible and surrounds the 10 m PFZ to protect its integrity. There was discussion on standardization of approach to using PFZ's and routinely allowing individual tree treatment within the 10 m PFZ.

Some operational foresters stated that the 10 m PFZ concept is interpreted and applied differently in the various areas of the province; there was inadequate standardization of approach regarding areas upstream of fish habitat. This shortcoming was identified as a major action item for DFO. A question was raised whether the 10 m PFZ is applicable to all waterbodies throughout the province. From a DFO viewpoint, it is not. The PFZ is only applicable to fish habitat, and immediate tributaries thereto. If information does not exist on fisheries values, however, the 10 m PFZ is assumed to be applicable to a waterbody, or ephemeral stream.

We discussed flexibility in the 10 m PFZ requirement upstream of areas of anadromous utilization or waters supporting recreational fisheries. It was determined that in upstream areas a 10 m PFZ would be a site specific judgement, based on the likelihood of downstream impacts in fish habitat and proximity. Another question raised related to the possibility of not requiring 10 m PFZs around ephemeral streams. Again, a site specific judgement is required, based on knowledge of the stream system, as well as the new information developed through the Carnation Creek project. Concerns based on Carnation Creek findings relate to (1) changes in litter production that might affect stream invertebrates, (2) cumulative water temperature effects, (3) changes in nutrient cycling in the soils, (4) changes in the riparian zone's ability to produce food for fish and aquatic invertebrates, and (5) any direct toxic effects on invertebrates and fish of over-spraying a PFZ.

Foresters want to know how far upstream from fish habitat can ephemeral and tributary channels be over-sprayed or sprayed with no PFZ with no harmful effects downstream. In many upstream areas it would be useful to foresters not to provide 10 m PFZS. How much information is required to judge the need for a 10 m PFZ in upstream areas? This remains a site specific judgement, but should be further studied. We concluded that the present guidelines with respect to PFZ and BZ had functioned well. They have protected fish and fish habitat, enabled the referral system to proceed, permitted foresters to use herbicides near streams, and allowed the public to be protected. In the future, we may wish to re-examine the extent to which 10 m PFZs are applied upstream of fish habitat, if appropriate data are developed.

Another area of inquiry that emerged from our discussions was the question of the BZ. A lot was said at this workshop about different application technologies (e.g. MICROFOIL BOOM). These are good opportunities to re-assess recommended BZ widths needed to protect the PFZ with these new technologies. Regardless of BZ width, there must be assurance that riparian vegetation and water quality are both fully protected. The PFZ, however, should be exactly that pesticide free.

There was discussion on whether the Carnation Creek Herbicide Project should be considered a worst case scenario. We were able to identify a number of reasons why it may not have been so. In the hydrology paper by Eugene Hetherington, for example, there was evidence of a significant amount of water on the site and plenty of rainfall. The impression given was that the herbicide that reached the stream was highly diluted. Had the soil been covered with frost or received heavy rainfall after an extended dry period, they might have found that there was less dilution. We also determined that since the stream flushed rapidly because of the high flows, the fish and other aquatic organisms in bioassays were exposed to even lower concentrations of herbicide in the streamwater.

There was discussion yesterday regarding determination of herbicide levels in water. We question whether it would be more representative to collect the analytical samples from the water column or the surface, where aquatic life may be concentrated, but also where the herbicide lands during an over-spray. There was a disparity between the theoretical calculated value in a stream overspray situation versus what was actually sampled experimentally.

## DISCUSSION GROUP #6 - AQUATIC ORGANISMS

Group Leader - Vince Poulin

The approach our group took was four-fold. First to review the objective of the workshop - which was information transfer; second, examine the conclusions and recommendations from each of the papers related to aquatic organisms; third, review current regulations to determine if a synthesis of the results would enable us to suggest changes in the regulations; and last, to identify areas of further research.

Given the manner in which the workshop papers were organized, no speaker presented an overview or summary of the research undertaken. Because of this, our first step was to summarize the results, then relate what we learned to our understanding of current practices. We tried to do this by asking several simple questions. The most important was whether the results were positive, negative, or had no impact.

### Temperature

Blair Holtby indicated that temperature had increased in the study streams, but only during the summer months. The phenomenon lasted for two years, but did not persist in winter and spring. As a result, the temperature increases observed did not have an adverse effect on fish survival nor timing of the smolt outmigration. However, it was noted that it was not possible to isolate potential cumulative effects of the small increases in summer temperatures on rates of detrital decomposition in the stream. An important issue discussed at length was the potential effects of even small increases in water temperatures on fish in streams located in the interior of the province where herbicides are being applied. In these areas, defoliation may have significant and substantive impact on stream temperatures.

### Water Quality

In dealing with water the results we focussed on pertained principally to fish. It was reported that conductivity increased 33%. These increases would likely have a net positive impact on stream productivity, as would the 20-30% increase in nitrates following herbicide application. With regard to the increase in nitrates, it was suggested that the typically positive effects of nutrient enrichment could be offset by decreases in fish egg survival. This possibility was highlighted by Scrivener in the workshop. We felt it important, however, to keep in mind that the increases reported following herbicide application were still only 20-30% of those observed after clearcutting. Stream phosphate concentrations doubled after clearcutting, and doubled again after herbicide application. Because phosphate levels were extremely low to begin with, we concluded the increases would have a positive effect on stream productivity.

### Periphyton

We then considered the information presented on periphyton. Periphyton is an algae that grows on the stream bottom and is used as a measure of overall stream productivity. Results showed some some short-term declines in periphyton levels, but these were later enhanced by increases in nutrient levels. Thus, we concluded the changes would have little effect on the stream ecosystem.

### Detritus

We focused next on the question on detritus, material derived from leaf litter that supports benthic invertebrate communities, otherwise known as litter-fall. While the herbicide treatment was not as effective in defoliating the targetted canopy cover as expected, there was significant, if not complete reduction in leaf litter, in the over-sprayed tributary. Measurements of micro-organisms and invertebrate communities in this area, however, indicated no significant changes in numbers or populations. The most important aspect of leaf litter discussed was its role in fuelling the food chains of coastal streams. The amount of food directly available to fish is determined by the detrital input to streams. Hence, preserving some level of detrital input to streams is a key issue among fisheries managers. It is quite obvious that several of our major questions relate to how much litter is required in small tributaries to maintain benthic food supplies and whether present practices involving herbicide use can ensure adequate supplies or would upstream sources be sufficient? Upstream sources may well be enough to satisfy the downstream needs of small streams or sections of streams.

In summary, there seemed to be little conclusive evidence presented that herbicide treatments had a negative impact on benthos populations in the study streams. On the other hand, it was emphasized that plants that grow in seasonally flooded swamps can be important benthos-producing areas and that despite lack of signigicant changes in benthos populations observed in the study, they are areas of concern to fisheries managers. This issue has led to problems between regulatory agencies and users. The group concluded that more research is needed to better quantify the importance of seasonally wetted areas to stream benthos production and to fish productivity in particular.

### Fish Populations

An important outcome of the study was the lack of any discernable impacts to fish. Relatively insignificant numbers of fish died, thus no differences were observed in survival following spraying. Three fish in Channel 1600 and six in channel 2600 were lost. No mortality or changes in weight were recorded in the resident fish populations, and no changes in timing of smolt outmigration observed. Studies of the acute toxicity further indicated concentrations of the herbicide were within a 10-fold margin of safety.

Overall, application of glyphosate in this study appeared to have only minor impact on aquatic organisms. However, issues such as loss of production in important seasonally flooded areas may need further exploration.

The above discussion occupied most of the group's time, but was considered necessary to narrow the results down enough to relate them to current practices. Hence, we didn't get all that far on current practices. Several of the group indicated there were problems with implementing the PFZ and BZ, particularly in regard to what appears as unnecessarily large BZ's and difficulties in locating PFZ's on hard-to-identify and hard-to-avoid back channels or ephemeral sites. There is a need for either a better planning exercise or better implementation of the existing one. Better operational monitoring and follow-up was also recommended.

The group also felt there was little flexibility in interpreting Section 3.31 of the Fisheries Act. For example, are PFZ's the targetted outcome of the regulations or are they being used to simply manage riparian zones for other reasons? The results of the Carnation Creek Herbicide Project suggested that the impacts of glyphosate application at Carnation Creek related primarily to reduction in vegetation and detrital production in streams. As a result, there was difficulty in defining BZ's and PFZ's and their functions. A key question left unresolved was - are PFZ's the management goal or are they to protect the riparian zones?

Two key areas of future research were considered worthwhile: (1) role of detrital input and benthic production from tributaries and ephemeral streams in maintaining fish production in larger streams; and (2) initiation of similar studies in the interior where small changes in temperature may have a significant impact on summer fish survival.

## DISCUSSION GROUP #7 - WILDLIFE

Group Leader - Harold Armleder

### Management Implications and Directions

Much has been said about the PFZ's (pesticide-free zones) over the last few days. It is a good concept that, for the most part, has worked quite well. In spite of the low toxicity of this particular herbicide, we did not feel that there was any reason to lessen the width of the PFZ as it protects valuable riparian habitat for fish and wildlife. However, we recognized the need for some flexibility in the PFZ concept on a site-specific basis and we want to emphasize that site-specific basis for flexibility. For example, some of the smaller side channels, which are perhaps not important for fish and wildlife habitat, and very difficult to identify operationally could be treated differently.

There is a real need to put things into perspective when considering the use of this and, indeed, any herbicide. We can't just think of these herbicide treatments in isolation and try to manage in relation to them. We have to recognize that there are all sorts of other habitat impacts to deal with, for example, harvesting, prescribed burning, and mechanical brushing and weeding. These different activities alter habitat in different ways; we have to recognize each activity and manage with the whole spectrum in mind.

Diversity of habitat is extremely important to many wildlife species. Good opportunities exist to reduce the impact of herbicide treatments on wildlife and habitat by giving more consideration to the temporal and spatial arrangements of those treatments to maintain habitat diversity. This should be considered in terms of all types of habitat alterations and not just those resulting from herbicide applications.

Areas of habitat that are extremely valuable to a particular species or group of species must be identified before any treatment occurs. For example, if there are wildlife trees that are of particular importance in an area to be treated, the method of herbicide application might be changed from aerial to ground-based application.

Much technical information was presented over the last two days but, for the most part managers were not given the bottom line. There is a serious need to transfer technical information into a form useful to field managers. This process has just begun and must be vigorously pursued if the full impact of the research is to be realized.

Communication must also extend to the general public. People must be informed about the safety of this herbicide, including the safety to the wildlife species that it may have an impact on, as well to human consumption of those particular wildlife species. If this is not done, the operational use of this treatment could be easily curtailed.

## Research Needs

Determination of the effects of herbicide on wildlife cover and forage is a pressing research need. There are a number of topics that need to be examined specifically. For example, the variability of the response, both within a plant species and among species, and the impact of the timing of application on various forage and cover species must be understood. The duration of the response must also be investigated. If there is only a one-year impact on cover and forage resources, the effect on wildlife will be vastly different than if the impact lasts several years. There is also a strong need to tie this research into the integrating framework of the biogeoclimatic ecosystem classification system. The responses to treatment at Carnation Creek may be quite different than those in some of the interior biogeoclimatic subzones.

There is a great need to investigate the impacts of herbicide in comparison to the impacts of alternative management options (for example, prescribed fire, and manual brushing and weeding). Because we live in a world where all of these treatments are commonly applied, we have to be able to judge the impacts of all the treatments on wildlife, thus placing the silvicultural use of herbicides in the proper perspective.

Wildlife can also have an impact on crop trees. When a habitat is significantly altered by reducing the herb and shrub component, there is a potential for certain species of wildlife to damage the remaining crop trees. This possibly must be examined.

It is necessary to continue with long-term studies on the lethal and sub-lethal impacts of this particular herbicide, not only to satisfy the managers, but also the public. A satisfied public is essential, especially when game or high profile species are involved.

The last point is not a research topic, as much as an approach to research. We must work hard at co-ordinating interagency research so that we get at the answers in the most efficient and timely manner. Often, by spending just a little more time and money, key questions related to resources other than trees, can be answered, if we plan for it at the beginning of the research program.

## DISCUSSION GROUP #8 - WILDLIFE

Group Leader - Sylvia von Schuckmann

### Conclusions

We started our discussions with a general look at the kind of research that was done at Carnation Creek, and whether or not it was clearly applicable to wildlife. We concluded that there was a fair bit of research done there which does have some implications for wildlife. And, in general, I would say that the interest in wildlife research elsewhere has been fairly recent. There has been a shift in interest from toxicology to habitat impacts, and I think that if you consider the types of information that have been presented at this workshop and the dialogue that has ensued in the discussion groups, you will agree with me that most of the concern seems to be shifting toward habitat impact.

One of the wildlife papers presented in the past 2 days was Alton Harsted's paper. He feels that this type of work is just a beginning. It is a snapshot, as it were, of what happened in a particular system with a particular species at a certain period of time, albeit a fairly short period of time. This is really an indication that there can be more work done in this area, not just with small mammals but with larger mammals as well.

A paper presented by Doug Pitt listed the variable impacts of ROUNDUP on different plant species. When many non-crop tree species (and there was some concern about the definition of crop tree versus non-crop tree), i.e. non-coniferous trees, are considered extremely valuable to wildlife, it is very important for us to understand the impact of herbicides on this vegetation.

In addition, the two papers that were co-authored by Hamish Kimmins were really of interest because they pointed out that this type of research does not generally produce good, usable results in a very short period of time. Habitat research is long-term research, and that means that we are just at the very beginning of it.

We talked a bit about whether or not one could draw some conclusion about potential changes to the way things are done in the field now, given the wildlife-related information that we have been presented here. We agreed that there was basically too little information on which to recommend changes in operational practices and operating regulations. A focus of future research should be to perhaps develop some guidelines that would usefully integrate forestry and wildlife concerns. This might mean, for example, some sort of compromise in harvesting systems or in using herbicides.

From our discussions about the 10 meter PFZ, our conclusion was that basically it was of high value for maintaining riparian habitats. It was stressed that riparian areas are extremely valuable not just for small mammals and birds but for ungulates as well. We strongly support that the PFZ should be seen as a guideline but there definitely should be flexibility to make site-specific adjustments where necessary.

## Further Research

We feel that, with research such as the Carnation Creek Herbicide Project, it is very important to take a holistic approach. And as we all know, when you are designing your uni-disciplinary research it is very difficult, but I think the payoff in the end is better than just doing little pieces here and there.

Again, our group underlined that there is more to silviculture than just herbicides. There was a real sense that perhaps more could be accomplished at the planning end of things, the pre-harvest planning stage, to perhaps obviate the need for using herbicides or, for that matter, any other vegetation management strategy down the road. Not only would this allow a better selection of treatment options and better long-term forest management planning but it would also allow comprehensive examination of the land management objectives, and integrated development of a plan which could minimize the impacts but maximize the productivity for all resources in the land base.

Research should be carried out in areas of high forestry value and high wildlife value, i.e., areas of potential conflicts, the resolution of which might lead to the development of operational guidelines. We must not only identify critical wildlife areas but we must also do research in these areas to understand wildlife habitat needs: critical ranges, riparian habitats, winter ranges and snag trees (or wildlife trees as wildlife biologists like to call them!). In B.C., deciduous trees can harbor up to 20 different species of wildlife per tree. This diversity is high compared to that in the rest of Canada and underscores our need to understand particular habitat needs.

While it is important to do wildlife research, it is important to not concentrate only on big game animals (on things that you can put holes into as someone said earlier!), but we must also identify and understand the habitat needs of small, non-game animals. We cannot ignore these fauna because of the importance of their interrelationships in the ecosystem, their role in the food chain, and their possible impacts on regenerating forests.

In a general sense, it is important to do long-term research on the functional relationships of wildlife to their habitat, to comprehend how the ecosystem components work together, to know how, why and for how long forest management affects wildlife habitat and wildlife, and to understand how to minimize those impacts.

We also stressed the need for research on basic plant succession, a topic of considerable overlap between foresters and wildlife managers. In relative terms, there is actually very little integrated forest ecology work done in this province; we find that quite distressing.

We feel that extension is very important. There are a number of things which can be done, not only for the operational people but for the general public as well. These include more workshops of the format experienced here today. The participants here are very enthusiastic about this method of information exchange and feel that it is very beneficial and healthy to get together with people with whom they normally do not interact, and to exchange ideas and do perception checks. We suggest that it is extremely important to get the available information out in circulation. One of the vehicles for the extension of wildlife habitat information, which has been very slow coming, is the wildlife habitat handbook.

And, lastly, our group suggests perhaps it is time in B.C. to have a riparian workshop to underline this very important habitat and valuable resource.

In conclusion, this whole workshop has been a very positive experience. The main reason appears to be that people are no longer concentrating on concerns about toxicology. We have moved beyond that stage to look at habitat impacts. This is a strong step forward, and I have a feeling that the general public might not be that far behind us.

## DISCUSSION GROUP #9 - FORESTRY

Group Leader - Dick Kosick

### Implications

Our discussions began with an assessment of the sequence of activities from logging to a free-growing plantation. As many of you know, we do develop, prior to the actual logging, a preharvest silvicultural prescription (PHSP) which indicates 2 and sometimes 3 years in advance what will be done to the area subsequent to logging. I know that some of the Forest Service people here would like to see us do one of these prescriptions for the whole five years of the development plan, but that is not possible. We are not that far advanced in our engineering or our forestry work, but we do succeed in achieving at least 2 full years of prescription.

After we completed this assessment, we tried to evaluate the opportunities for implementation of the research findings and to identify further research needs. Our group found that there were a few opportunities for operational changes based on research results. Kimmins mentioned the importance of nutrients, nutrient regimes and nutrient cycling, and pointed out that burning some areas could result in a loss of as much as 1200 kg per ha of nitrogen. We all have seen areas where this type of damage from fire has occurred. Our group suggested that, where opportunities for choice exist, and consideration is given other resources, it may be preferable to use herbicides instead of prescribed fire. At the PHSP stage there is opportunity to incorporate considerations of nutrient regimes. In other words, based on nutritional considerations, a forester can decide at the PHSP stage whether he will burn the cutblock or mechanically prepare it or, perhaps, opt for herbicide use.

I think it is important to do a better job of communicating, to the public, the nature of the forest management options available to us, and the probable consequences of selecting particular options. Perhaps, if we did communicate a bit better in a language the public understands, and if we did emphasize integrated resource management, we might not encounter quite as much opposition to forest management practices, in general, and the use of herbicides, in particular.

As an example of poor communication, an open opposition to the use of fertilizers in forestry operations has been displayed because of the assumption that the people who live in that watershed will suffer from nitrate poisoning. There is an actual campaign on the east coast of Vancouver Island against fertilization right now.

Another thing which we have gleaned from the opportunities for implementation of research findings would be the timing of application, which is certainly different for rehabilitation areas than it would be for plantation release. Another aspect that I think we should all consider is that total elimination of competing vegetation is not essential. In other words, a 60-70% alder kill or a 50% kill of salmonberry might be adequate to release the plantation. Quite often in the past, our objective has been to eliminate all the alder, for example, but we tend to look at things a bit differently now.

## Further Research

The other objective was to see what further research is necessary. Foresters still have to select those areas targeted for herbicide treatment. Our conclusion was that we do not have enough efficacy and screening trial information to be able to make that decision accurately for every area. There is still some question as to actual dosage required. Is a dosage of 2 kg/ha actually the right dosage? Can we get by with 1.5 or 1.25 kg/ha? There should be more research done on the question of timing of applications as well. The effects of height of the target species on treatment efficacy, survival and growth response of crop species, and, as some previous speaker mentioned, the impact of the surfactant are questions that were not dealt with adequately at this particular workshop. We should know the toxicity of the surfactant so we can determine whether in fact we can alter the herbicide : surfactant ratio for efficacy or economic reasons. Of course, in his planning, the forester must consider the overall economics of the treatment and, perhaps, a need for repetitive treatments. He may opt for one treatment which is quite inexpensive but may find down the road that he has to repeat that treatment again and again.

We are not doing a good enough job of communicating and taking advantage of all available information. For example, I did a little research on alders recently and found that there were at least 400 articles published on nitrogen fixation in forestry. It would be interesting to have someone collate and summarize this information for the operations perspective. I would like also to see a flow chart illustrating the pathways of herbicide through the environment; e.g., if one applies 2 kg of active ingredient per ha, what is the fate of the herbicide, how much is intercepted, how much ends up in the soil (and if it does get into the soil, what happens to it?), how much leaches out, how much is transformed and what are the degradation products?

We must continue and improve technology transfer to the operational people (i.e., timber managers, foresters and engineers), and to the public. In conclusion, our group recommends:

(1) a group interpretation of scientific results, and application and testing of these results in the field;

(2) further technology transfer take place in all aspects of herbicide use and resource management; and

(3) further research in the areas identified.

We would like to say that we found the work of this workshop to be very constructive and very positive.

# DISCUSSION GROUP #10 - FORESTRY

Group Leader - Wayne Coombs

There was a wide cross-section of participants in our group. Within that cross-section we had individuals who had used herbicides (ROUNDUP and others) quite a bit and there were some who did not have any experience in herbicide use. But, we also had a good representation from a range of agencies, which allowed for a good discussion. We felt that this was the advantage of these group discussions, that we were able to establish, on a one-to-one basis, good credibility and rapport. I think that this is really what resource management is all about, working together as a team.

We initially established that the major objective of the Carnation Creek Herbicide Project was not to examine herbicide efficacy for forestry but was to assess the environmental impacts of operational applications of ROUNDUP. Further to that, we discussed the Carnation Creek study in detail and one of the things we felt was that, although there were results similar to those from other operations, there were limitations to the experimental design. Again, as we know, the emphasis was towards assessing environmental impact, but we felt that there could have been more of a comparison of various treatment tools. Using the MICROFOIL BOOM and not comparing it to the conventional tools that we are using right now limit the applicability of the results to other operational contexts. We feel that there is some question on the efficacy of the MICROFOIL BOOM technology and its applicability to cutblocks of varying sizes, shapes and terrain. We concluded that the Carnation Creek herbicide study had minimal operational value for field forestry because of the lack of the comparison of different treatments (both herbicide and manual), treatment intensities and timing.

We think that there is a tremendous need to have research results more available and more readily communicated. There is a diversity of research being carried out, and there is a need to coordinate the dissemination of information from these research projects.

We felt strongly that, in the study reported by Nick Payne, there would have been some value if there had been some on-target evaluation at the same time as the assessment of the off-target drift from the three booms. This may have reflected the lack of coordination of research efforts, but in any case, the result was a loss of valuable information in B.C. relative to deposition on-site as well as off-site.

Relative to Kimmins' study, we felt that nutrients are very important not only for crop trees but weed species growth as well, and this is one area which has to be addressed in future research. We voiced a concern that the interpretation to be derived from Kimmins' study is that no burning should be carried out. We thought that this was not the real message. A lot of sites that are burned have plenty of nutrient capital and appear to suffer little, if any, long-term impact. Other sites are, of course, much more sensitive. We are suggesting that we should evaluate the sites during the development of the PHSP and burn only those sites which are nutrient-rich and will not suffer irreparable damage. Because burning in many areas is a very valuable tool for reducing brush competition and increasing the number of plantable spots, we must have the capabilities of predicting possible fire impacts and of altering treatment strategies accordingly.

In evaluating Raj Prasad's paper, we felt that there was a need to better assess treatments and time of treatments on conifers by correlating these to seedling morphological features (e.g., bud development, thickness of wax, woody tissue development in shoots, and physiological condition of the target species). In other words, in order to better protect the conifers from herbicide damage, we need to know at what points in the growing season the morphological state of the seedlings will be most resistant to chemical damage, and, to more effectively control or eliminate the weed species, we need to know when they are most vulnerable to herbicides. This information will lead to more timely and efficacious treatments.

From all the papers that were presented and other papers we have heard in other workshops, we perceive a need to standardize methods of assessment of the effects of herbicide applications. Without standardized protocols, the comparability of research results and the transferability of results and interpretations will be seriously impaired.

With regard to buffer strips and PFZ, we concluded that the information provided by this study was inadequate to formulate any judgments as to efficacy and best uses of buffers. We recognize that buffer strips and PFZ restrict our capabilities to carry out forestry operations in areas where small tributaries and ephemeral streams occur. How critical are these areas in receiving and transporting herbicide downstream to fish-bearing waters? We should be providing fisheries staff and other agencies with the decision-making information to evaluate the treatment of minor side channels (i.e., rates and volume of flow, resource use(s), slope overhead vegetative cover) to allow overspraying. We need guidelines as to which streams can have PFZ restrictions lifted.

We concluded that there was a definite need for the testing and registration of new herbicides for forestry in B.C. It is interesting to note that this need was also identified by not only the foresters, but by other resource and regulatory agencies. We think that research is needed to address herbicide efficacy in forestry and environmental impacts (including those related to sublethal effects on fish and wildlife). There is a need for full involvement of all agencies in this research. The Carnation Creek Herbicide Project was a good example of a group of various agencies and resource users that worked together and developed a positive working relationship.

While there is quite a bit of forest ecology research underway, there is little research directed towards the autecology of competing species of vegetation. I can name only 2 or 3 studies, all of which are being carried out under FRDA. But the autecology of weed species is one area that the group felt should be addressed to better understand the weed species and their ecological capabilities and how various treatments affect those species.

Another major point raised related to the transferability of research results and interpretations, i.e., how are the Carnation Creek results to be extrapolated to other areas of B.C.? Can we actually transfer this information to other geographical areas and avoid having to carry out similar studies in the interior? Or do we have to invest in additional studies?

# DISCUSSION GROUP #11 - SPRAY TECHNOLOGY

Group Leader - Dan Cronin

## Major Observations

Our first major observation related to the value of the MICROFOIL BOOM within the context of current operational practices. It was felt that the MICROFOIL BOOM had rather limited application on a broad scale operational basis. Some of the limitations were that it was slow in delivery; it required high volumes for application, thus making it expensive to operate; it has questionable availability (we were led to understand that they are not being made any longer and there may be some difficulty in procurement); it is characterized by large droplet sizes, which decreases efficacy; and its usage over broad areas has been plagued by some stripping and skipping. We felt, though, that there is value and potential for the MICROFOIL BOOM and the thru-valve-boom (TVB) systems for use in sensitive sites, perhaps along the PFZ or water beds to be protected. This potential is increased because indeed a single application delivery vehicle, a helicopter, can be fitted with convertible systems. The use of boom systems in research, I suppose, could be defended in that they are a more controlled system of delivery with higher accountability. We had some agreement that in operations such as the Carnation Creek study it was acceptable and therefore may be used again.

The second major observation was that these studies have direct implications on our maintenance of what we have called the PFZ, and are also related to the BZ, which is more frequently referred to in the papers delivered. One implication of Nick Payne's work in particular is that a no-deposit zone is unattainable. Even with drops of 3 mm he was finding deposits 200 m from the edge of the spray swath; depending on the methods of detection, deposits could be found even further away from the target. The 10 m PFZ concept, therefore, has more or less been exposed as being arbitrary and unscientific. There was really no dispute that we could not maintain a PFZ as pesticide free. There will therefore be continuing pressure against the concept of a PFZ and the terminology used.

The risk in maintaining the PFZ concept in current management practices is that we could lose credibility in the eyes of foresters and the public when this information is disseminated. The value of maintaining the status quo with respect to the PFZ concept in current management practices is that it has operationally maintained a safety margin or at least the appearance of a safety margin that has been comfortable to deal with, at least from the standpoint of the public and perhaps some resource managers. The other implications of removing the PFZ requirement appear to be somewhat onerous, but we did not get into those.

## Recommendations

The primary recommendation the group made was that we need guidelines based on science that can identify, for the practicing forester, the buffer zones (including PFZ) which he can likely achieve under the varying range of conditions and equipment presented to him. The studies we were presented gave us several, rather specific circumstances, with only a few pieces of equipment used. But there is a much broader range of field conditions and it would be useful to develop a matrix for the selection of buffer zone specifications, which could be then implemented. This could be essentially either an operational research compilation or a research program in itself.

The second recommendation is that some additional form of training for applicators be introduced so that there could be greater confidence in their ability to maintain the BZ and PFZ that are required. We recognized that the Ministry of Forests and Lands and some companies have higher standards of experience that must be met before one becomes an operational manager, but this was not considered universal and there is lots of evidence of mistakes being made.

The third recommendation for continuing agency dialogue relates to the PFZ and BZ guidelines themselves. We feel it is necessary to maintain discussions on the BZ and PFZ concepts in relation to the equipment, methods and approaches that are being developed in order to keep the concepts current and useful for field operations. The suggestion was made that the guidelines could be incorporated into fisheries/forestry guidelines as they are developed and introduced.

The last recommendation is that the restrictions for the protection of water bodies per se were too absolute and needed some defining. In some cases, wet footprints and temporarily filled equipment tracks were defined as water bodies although, rationally, there appeared to be no need to avoid them. Therefore, a need exists for a further defining of water bodies needing protection to deal with some of this uncertainty.

## DISCUSSION GROUP #12 - SPRAY TECHNOLOGY

Group Leader - John Henigman

We identified very quickly that we failed to see how this workshop had a lot to do with the technology of spraying. Specifically, droplet sizes, the booms, nozzle sizes and so on really were not discussed. The implications certainly were discussed but not the technology per se. However, we decided very quickly, almost spontaneously, to talk about the process whereby one comes to spray an area and how one does that.

### Issues

We put together a list of concerns and ranked them. The first concern relates to water bodies. We must be able to identify where they are and their importance in the scheme of things. We were told that fisheries habitat can in fact be dry, not a water body at all. On the other hand, run-off channels, which in fact are so remote from fishery-sensitive water bodies, do not require any protection at all. So, we identified a spectrum of what might or might not be habitat, and yet conceivably all such areas might require buffering. On the other hand, very valuable habitat might not require, under the legislation, any buffering at all. We feel that operational personnel, both fisheries and forestry staff, should be assisted via FRDA to specifically detail habitat and determine the needs of buffers on that habitat. So meetings such as this, or ways of facilitating operational people meeting on the sides of streams and coming to some understanding would be very useful.

The second concern was BZ and PFZ. There was not any great amount of discussion about whether or not the concepts are appropriate, but certainly where they are going to be applied was at issue. It is important to differentiate between different herbicides: ROUNDUP we have talked about, but we have not talked about GARLON at all. There are certainly other ones we could talk about, and all of them have different parameters and possible effects and impacts.

It is also important that we consider differentiating between habitats; i.e., what needs protection and how should it be protected. We recommend that regulatory processes be changed to allow maximum flexibility in determining need and extent of buffers, and to assist field staff in facilitating regulatory changes and writing guidelines. So, in the most extreme case, tackle the basic legislation that creates an overburden on regulatory and operational people; free them up so that they can make tangible, practical decisions on-site about a specific program. So, perhaps the Pesticide Control Act, possibly the Forestry Act, and possibly the Fisheries Act, all of those regulations which demand that there be no flexibility, should be loosened somewhat to incorporate guidelines which allow flexibility and some direction.

**Spray Hardware**

Contractors conducting aerial spraying should have available, on-site, different kinds of booms and nozzles to handle a job effectively. For example, if a MICROFOIL BOOM or a thru-valve boom (TVB) would facilitate achieving the BZ and PFZ requirements, they should be available to do the margins of particularly sensitive areas. The rest of the site could well be sprayed with a conventional, hydraulic, nozzle boom. This flexibility would be quite cost-effective. Perhaps FRDA could facilitate aerial freight contractors acquiring these specialized types of booms and allow the forest industry across the province to have these available. We feel that there is definitely good reason to want to enhance: (1) site-marking methods, i.e., how one defines the boundaries so that the applicator knows where to spray; (2) swath-marking methods, so that in effect the applicator doesn't have problems with skipping, overlapping, or restarting when finished refilling; and (3) spray monitoring methods, all of which are pretty shoestring at the present time.

The ability and the opportunity of the forester to direct the pilot while he is spraying are paramount so that all concerns are met and the quality of the operation is enhanced. It would be nice for the spray supervisor to know that, when the helicopter disappears over the hill doing his work and the spray supervisor is left in the blind, the pilot is going to do as directed.

## DISCUSSION GROUP #13 - SOCIAL CONCERNS

Group Leader - David Bowering

**Risks**

First of all, we looked at risks, but the people in the group actually did not think that there were any risks associated with herbicides, glyphosate in particular, in view of the science that we had seen and the regulatory process in place. The consensus was that there were not significant risks, but there were risks related to the public's perception. Some of those perceived risks result in economic risk: the allowable cut is related to the ability to efficiently manage the forests now; herbicides are part of the management strategies required; and, thus, jobs in the forest sector now depend on the use of the herbicide tool. There is significant risk to the economy. The public perceptions are not appropriate -- people do not perceive the situation as it actually is.

There are political risks, in the sense that issues blow up and public pressure mounts. There may be irrational acts that have a negative impact on the ability to manage forests. There are some marginal concerns in terms of direct risk. People who actually are working with and applying herbicides are most at risk. It is important to minimize risk and to not be complacent in relation to herbicides. Another marginal concern relates to accidents when herbicides are being handled and transported (i.e., concerns about spills contaminating the environment). But again, the ability to effectively manage the forests is really at risk because of perceptions, not because of serious concerns about the toxicity or serious environmental impacts of glyphosate. Normal precautions have to be taken both from the public perception point of view and in terms of real safety.

### Perceptions

The main problem area seems to be public perceptions. People talk a lot about trust, that there has been a breakdown of trust. Does the public trust foresters and, in fact, do the foresters trust the public? The consensus was that we probably do trust one another. Most people are reasonable except, perhaps, for a small percentage that can never be reached.

It was pointed out that the pesticide appeal process can establish a conflict situation. We saw a need for more public input to the process before both managers and concerned public are backed into corners in conflict situations. Our group felt that there are a lot of old ideas still prevalent, making communication with some people quite difficult.

There has been a tremendous growth in silviculture and intensive management, new ideas that the public still does not fully understand. There is a lot presently being learned but we are in a transition period during which we can expect some rough going. We do not have a lot of long-term experience in silviculture and intensive management. There has not been an opportunity to really build trust over a long period of time. Hence, we are in a trust-building phase.

In terms of formal and public education, it was felt to be important that scientists portray a balanced picture. There is some serious concern that right now they do not, that instead of a balanced forest management perspective there is some anti-herbicide bias which will, if not corrected, lead to future problems. This again emphasizes the idea of relative risks and distorted perspectives on the part of the public about how dangerous things really are. From my point of view, smoking is the major example of a very serious risk that people generally underestimate. The idea that Johnson's Baby Shampoo might be as irritating to the eyes as glyphosate was raised; there was also some discussion as to what is the better shampoo!

As you all know, in traditional Chinese medicine, green is the color of wood and it is also the color of healing. We are all Chinese practitioners in a way, and I sense in this area that there is a healing process going on. There has been some damage in terms of the public and forestry, some pain and some conflict, but I think there is a definite healing process taking place.

### Solutions

Some solutions were suggested for spreading the educational message and improving the perceptions. Workers on the ground need to be convinced in terms of efficacy and safety. People actually working in the field apparently do not all feel comfortable with what they are doing. That may be a place to start with the educational message. The positive message to the public is now starting to be delivered. "Forests Forever" received a number of strokes as a positive move, although there was some concern that the message be balanced, that we not try to convince people that everything is perfect and there have never been any mistakes made.

At the local level, things such as tours of forests are effective. It was pointed out that conflicts often disappear when people get out on the ground and see things in a realistic perspective. Videos of forest management strategies and practices are helpful when informing local interest groups. Some of our group suggested becoming involved in environmental interest groups because, at heart, we are all environmentalists and we really do share a common interest. There really is no reason why people should not belong to these groups and hopefully balance that process and perspective.

An interesting idea was proposed to inform people about herbicide treatments in areas where environmentalists and concerned people would accept them. Posting would stress positive management goals, and not convey a message of "black death".

Appropriate formal education is required but there was not a very strong sense of optimism that it could be achieved. Would it be possible to have applied science and resource management considerations in the curriculum for students in the province? Would it be useful to have public input to land classification (i.e., resource use planning) as opposed to land management?

We feel that understanding and practicing the principles of conflict resolution are important. We had somewhat of a demonstration, I would say, in our group, given its diversity of expertise and interests. If one could come to understand his opponent's position(s), many conflicts can be dealt with fairly and expeditiously, particularly in a heavily emotion-laden atmosphere. It is important for people involved with the public in this area to seek such training.

## DISCUSSION GROUP #14 - SOCIAL CONCERNS

Group Leader - Paul Pashnik

### Issues

We had a wide perspective in our group and a good discussion. We discussed many things that Dr. Bowering talked about, and it was interesting that we had only one paper that dealt directly with our issue, and that was his. However, I think all the papers had implications on the whole issue of social concerns because of the lack of public awareness and the credibility of test and safety data with respect to health and the environment.

Public perception was deemed to be one of the biggest problems when dealing with herbicides: fear for the health, safety and environment of citizens. Pesticide safety and test data are restricted and are apparently difficult for the public to obtain. Public trust is a problem: are the government regulators living up to their responsibilities? Bad press has, justifiably, been caused by such major environmental issues such as DDT and 2,4,5-T and by credibility problems we have had with falsification of efficacy and test data (I.B.T. Lab.) and related court cases. But, when misconceptions are printed by the media, (e.g. "---2,4-D is Agent Orange", "ROUNDUP" causes cancer) there appear to be no response from experts in the industry to correct the obvious errors or to set the record straight. We also dealt with the ethics of forest management and felt that really there was no validity to any concerns raised. The main concern was that the public perceives pesticide use as a profit motive, and perhaps political commitments to both forest and chemical companies.

We looked at risks--risk to the environment, risk to health, and also the lack of risk-comparison data. Such information is needed when we are explaining the levels of risk associated with different treatments or practices. There is very little risk-comparison information in B.C. The forest industry has avoided discussing this topic due to lack of such information. There are also serious risks to successful forest management in not using herbicides. We will continue to create excess backlog NSR (not sufficient re-stocked) lands and lose forest sites by not using herbicides on many land areas where such treatments are the only effective vegetation management tool available. This will have a direct reflection on industry costs and long-term sustained yield and, of course, the economy, in general.

We also identified forest land use planning as a problem. We felt there is a role for the public in B.C. in the broader planning context: e.g., in timber supply area planning and TFL management working plans. This public role should not be overlooked or glossed over; this is where we can openly discuss the various land use and management options, and consider and accomodate valid public opinion.

We also discussed the misconception that, perhaps, the forest industry is in its 'sunset' stage. Many people believe this and it has not helped that this misconception has, in the past, been supported in part by some uninformed provincial politicians.

## Conclusions/Recommendations

We came up with a couple of conclusions/recommendations:

1) Public perception is the biggest problem that we have to address. Accordingly, we require a pro-active public information program. This program should define vegetation management alternatives and ensure that the public is presented with the costs and benefits; the risks and how risks are minimized -- this would involve a brief explanation of the chemical registration process, the application for pesticide use, pesticide permit issuance, the appeal process, and the requirements and standards we have in staff training and project control.

2) Our next recommendation related to emphasizing the judicious use of herbicides based on site-specific prescriptions. Herbicides should be used where they are the most biologically and cost-effective tool; and where alternatives such as prescribed fire, manual brushing or mechanical site preparation are not viable vegetation management options.

3) Pesticide public information centers should be developed to provide reference materials, skilled communicators, demonstrations, videos, etc. These centers could be developed in association with demonstration forests, for example.

4) We recognized the need for resource planning and a continued commitment by government agencies and the forest industry to integrated resource management. A better exchange of information among resource users would produce better resource management plans. Workshops are a good forum in which to exchange information, work on problems, and identify solutions.

5) The public must be involved in the resource planning phase. TSA and TFL management and working plans should be made available for public review and comment. Pesticide use and alternatives should be clearly identified. If such information is contained in development plans, those plans should be then similarly made available for public review and comment. To accomplish this we felt that we should use existing TSA and TFL planning procedures (management and working plans and development plans), organizations and individuals.

6) We individually should be proactive and become more involved through responding to inquiries, being guest speakers at annual meetings and conventions where the whole forest management picture can be explained, including the scope and importance of the pesticide option for vegetation management. We must remember to use simple, layman's language when we are talking to groups, citizens, city councils or municipal water boards.

# CONFERENCE SUMMATION:

# THE CARNATION CREEK HERBICIDE TEST WORKSHOP

Mike Halleran

Communications Director
B.C. Wildlife Federation
Box 1090
Kaslo, British Columbia
V0G 1M0

Ladies and gentlemen; this has been a long three days. Have you ever felt that you were drowning in a sea of words? I think it was Phil Gaglardi who once said that the mind could not absorb any more than the backside could endure. As a former press gallery reporter I used to spend every day listening to long speeches and in the last three days we have heard some that were good and long. And some that were more long than good.

It is now close to mid-afternoon on our third day and I notice that our numbers have thinned out a little. Obviously, not all people have an equal ability to endure prolonged pain. I was wondering about those people who left early. It looked like an interesting research opportunity so we monitored those early leavers to see whether there were more forestry or fisheries people among them. But alas; "The results of our research were inconclusive and further study is required.'

Whenever I am asked to be the sum-up speaker at a conference, I usually try to refer to all the papers individually. This is not possible in this case (with about 25 speakers) so I have had to take a different approach. I listened to as many of the presentations as possible: I floated through the various workshops and I read all the abstracts. As usual, I took far too many notes and had to distill them considerably in order to stay within my alloted time. I have three topic areas, which in my judgment have emerged as highlight impressions after being among you for the last three days. They are:

1. The quality of the presentations and the effectiveness with which they were delivered.

2. The conclusions gained after listening to the presentations.

3. This observer's prognosis for putting your findings into practice.

I find it necessary to say something quite critical of many of the presentations and the way they were delivered. Many of the presenters delivered a fairly thoughtful abstract but then chose to ad lib through some fairly tedious elaboration, frequently (if not well) supported by a number of badly produced slides. People at the back of the hall found some of the text unreadable. There were some fascinating papers and some were quite superb. But on the whole, I found the standard to be disappointingly low. And someone should tell the hotel that this public address system is quite inadequate. If you have trouble seeing the slides and can't hear the speaker--frustration is understandable. A lot of the speakers wandered off the microphone thus shutting out people at the back of the hall.

In trying to draw some conclusions from the presentations, I had a sense of both optimism and dismay. We might as well get the upbeat stuff out of the way first. The managers who thought of using Carnation Creek as a herbicide test site are to commended. Having a field project of such long standing, with its accompanying huge data base, made possible the kind of test that emerged with a credibility which could not have been equaled elsewhere. Research findings from Carnation Creek have high credibility and with good reason.

Having heard so many attacks upon forest herbicides it was interesting to be given so much "good" news. I have to point out that I reside in a part of the province where herbicide protest has included public demonstrations, civil disobedience and vandalism. This has been directed at testing, let alone application. Yet, the biogeoclimatic conditions are quite similar to those at Carnation Creek. I refer to the interior wet belt, the cedar-hemlock zone, known also (by the blizzard of signs around the region) as a "pesticide free zone." Regardless of the signs, the west Kootenay, like every other place on earth, is far from pesticide free.

Partly as a result of agitation from the west Kootenay, the debate over herbicide use is now highly polarized. To me, it is an example of the kind of pendulum politics for which the region is widely known. It will thus be fascinating to see what influence, if any, the Carnation Creek findings will have on the provincial herbicide debate. Even at this conference, while there has been a quite high level of statesmanship during the sessions, once into the conversational exchanges, it turns out that the veneer is fairly thin and in a few cases special interest bias sometimes transcended both reason and good manners.

In general, public fears about aerial spray of herbicides in the forest revolve around the following:

There are fears: that spray from aircraft is so imprecise that sprays will drift over vast areas, that rainfall and run-off will leach residues into streams, etc., with deadly results, that the spray will accumulate in the soils, etc., etc.

The use of glyphosate in the Carnation Creek tests revealed that most of these fears (at least with this particular chemical) were groundless. When this chemical (trade name ROUNDUP) is applied in the concentration used in this experiment, and with the technique of this helicopter spray method, the impact on the environment was not only short-lived but confined to the target area and the aftermath was quite minimal if even detectable at all.

One aspect of intensive management is predator control: to increase a harvestable surplus by controlling competing species of plants or animals. Brush or "weed" control in forestry is one example. It is sometimes criticized by fish and wildlife interests, a puzzling response since they themselves frequently engage in the same process. Killing the natural predators of salmonids or terrestrial animals like elk and deer has a long history in B.C. and one which is strongly opposed by the general public. Should predator control be re-introduced for sea lions and seals, public opposition will certainly intensify. The furor over killing a few wolves is proof of that.

In fact, the use of chemicals to kill unwanted competitor species was not started by foresters but by fish and wildlife managers. They were the real pioneers. In the 40s and 50s the wolf was virtually eliminated from southern B.C. Wolf and lake poisoning both required the use of deadly chemicals such as cyanide, strychnine and toxophene which had a toxicity that would make ROUNDUP look like Mom's chicken soup. These poisons (that's what they are) have been widely used in B.C. British Columbia lakes are still being poisoned, now using chemicals that are described as "safe."

Obviously, there is now a higher standard of awareness that real ecological risks are inherent in maximizing single plant or animal species. While zoning land to "highest and best use" is often the best choice there are obvious reasons to oppose province-wide monoculture forestry with its unattractive image of some kind of coniferous cornfield. But if maximizing a few species is deemed ecologically inappropriate in forestry it would seem no more attractive in wildlife or fisheries.

Now to the third point: whether or not the Carnation Creek herbicide test results are likely to mean that public fears of ROUNDUP are alleviated. I think that will depend on whether you people get really serious about reaching the public with this information and whether you speak with one voice on the subject. If unanimity is lacking, these findings will be less likely be accepted. The forestry establishment has been saying (for years) that ROUNDUP, properly applied, was safe for use in intensive forestry. These tests would seem to confirm that. Now it is up to the various special interests in the discussion to make some collective public statements about the matter. **The information from these studies must be condensed into a single information package, prepared for lay readers and distributed widely.**

Some scientists conducting research at Carnation Creek used a procedure that is widely followed in gauging the results of ecologically sensitive activity. They used a so-called "worst case" scenario, projecting results to encompass the worst possible consequences. In considering the public acceptability of these findings I thought I would also pose a "worst case" scenario. This could apply should the question of forest herbicides become more political, as I think it will. Here we go. If there is not an appropriate move to inform the public of these findings, I think there could eventually be a ban on forest herbicides in B.C. In fact, from my own perspective (and barring the kind of major information effort that I have described) I think a B.C. ban on forest herbicides is not only possible but likely.

I would also observe that many of the people currently coordinating herbicide research information are naive politically and fail to recognize the zealousness of the anti-herbicide and anti-logging factions and how sympathetic media is to their cause.

Earlier this year (1987) delegates to the BCWF annual convention voted in favor of a ban on the aerial application of pesticides[1]. At the convention in 1988, there will likely be a motion to have that resolution become part of Federation policy, meaning that the Federation will be required to campaign accordingly.

A ban on forest herbicides would have virtually no benefit to the environment for two reasons. No. 1: the forest use of herbicides is only a fraction of the volume used in agriculture. No. 2: (as we have learned at this conference) at least one forest herbicide (ROUNDUP) is so benign that even when sprayed directly over a stream channel (containing resident coho fry) no unusual mortality was observed. But that does not mean ROUNDUP will never be banned. Banning herbicide use would have a great and **negative** impact on intensive forestry. It would be like banning all predator control in fish and wildlife programs, a move that would cripple current management objectives and result in drastic cutbacks in hunting and fishing seasons.

If herbicides were banned from use in the forest, the benefits of intensive forestry would be much reduced. The Falldown Effect[2] would happen sooner, sag deeper, and our climb out of it would take longer. In fact, we might never fully recover and could find ourselves forced to accept a much lower allowable cut for a much longer period of time. WHY SHOULD A WILDLIFE

---

[1] In this sense the word "pesticide" refers to herbicides and fungicides as well.

[2] A drop in the allowable cut caused by removal of the first growth forest before the second crop is ready. The falldown effect can be greatly offset by intensive forest management.

ADVOCATE BE SO CONCERNED ABOUT THAT? Because a failure of the intensive forestry program will **absolutely** result in increasing conflicts over fish and wildlife.

It needs to be stressed that herbicide use is intended to be very site-specific and that manual and other non-chemical treatments will still predominate. And more people need to become aware that the **amount** of herbicide used in the forest is almost insignificant compared to domestic and other industrial use. Agriculture is the big user and it is doubtful if forest use will ever equal the amount used on private lawns and gardens.

With all renewable resources, there are times when the natural processes are the best choices and all agencies should continue to stress that. Moreover, the pressures to manage all renewable resources more intensively comes not from the resource **managers** but the resource **owners**. Public demands for all the values of the forest: including range, recreation, fish and wildlife, are rising and the moves toward intensive management are in direct response to that. This was a technical, not a sociological conference but these factors lead to the political action that really drives the game and thus have to be considered as well.

Overall, this conference has been in keeping with the high standard of technical excellence that we have come to expect from the Carnation Creek project. I choose to end this somewhat unconventional summation in an equally unconventional way (at least I am being consistent) and I do so by sharing with you a piece of thought-provoking B.C. poetry.

The work is by Peter Trower, a former coast-logger. And while it was written with an artist's pen, it includes some very sound ecological perceptions as well. It is not delivered for editorial purposes but as a reminder of the very high level of emotion and sensitivity that some people (loggers included) have for the functioning, giving and renewing forest. The poem is called "THE ALDERS."

The alders are the re-occupiers.
They come easily and quick into skinned land:
Rising like an ambush on raked ridges:
Jabbing like whiskers up through the
Washed-out faces of no longer used roads.
The alders are the forest-fixers.
Bandaging brown wounds with apple-green sashes:
Filling in for the fallen firs:
Jostling up by the stumps of
Grandfather cedars: leaning slim
To the wind by logjammed, logger-left streams
The alders are the encroachers.
Seizing ground the greater trees owned once
But no more.
This is the time of the alders.
They come, like a bright upstart army
Crowding the deadwood spaces: reaching
At last, for the hand of the whole.
Uncharted, sun.

Once again, thank you for affording me the opportunity to be both chairman and summation speaker at this important conference. Thank you for coming. Merry Christmas to you all. These proceedings are now adjourned.

# A SUMMARY OF CARNATION CREEK HERBICIDE STUDY RESULTS

P.E. Reynolds[1], J.C. Scrivener[2], L.B. Holtby[2] and P.D. Kingsbury[1]

[1] Forest Pest Management Institute
1219 Queen Street East
Sault Ste. Marie, Ontario
P6A 5M7

[2] Fisheries and Oceans Canada
Pacific Biological Station
Nanaimo, B.C.

## ABSTRACT

The Carnation Creek Watershed, located on the west coast of Vancouver Island, was aerially treated with ROUNDUP (glyphosate) from September 6 to 15, 1984 with the intent of examining environmental fate and impact of ROUNDUP treatment on a temperate coastal rain forest. Carnation Creek presents a unique research situation: we possess a 20-yr data base on its salmonid population. This data base has permitted whole life history impact assessment of the effects of numerous forest management practices, including the possible impacts of herbicide use on this resource.

Following ROUNDUP treatment at Carnation Creek, various chemical and biological studies were conducted for up to three years post-treatment. These studies revealed no unexpected or long-term adverse effects on coho salmon or other aquatic organisms using tributaries that had been directly oversprayed with the herbicide. Residue movements within the watershed and residue inputs into the aquatic ecosystem were carefully monitored in relation to autumn and winter storms. Glyphosate residues rapidly dissipated and degraded in the natural environment. After one year, remaining residues were strongly adsorbed to organic matter, soil particles, and/or stream bottom sediments, and were deemed to be biologically unavailable.

## INTRODUCTORY REMARKS

In the spring of 1984, ROUNDUP (glyphosate) was federally registered for forestry use by Agriculture Canada. Although in-depth environmental impact and fate research had been conducted with glyphosate elsewhere in the Pacific northwest (Newton et al. 1984). Provincial and federal regulatory officials in British Columbia expressed concern about issuing operational permits to spray ROUNDUP in the coastal zone. The environmental conditions of the cool, temperate rain forest of coastal B.C. (Table 1) are different than those in the more arid, warmer forests in southwestern Oregon, where previous research had been done. There were also lingering federal and provincial concerns about possible short-term fish toxicity of the surfactant used to formulate ROUNDUP.

Table 1. Carnation Creek Watershed characteristics

- high annual rainfall, 2,100 - 4,800 mm
- steep slope
- frequent storm events
- seasonal flooding
- cool temperatures
- soil: highly organic surface horizons; well-drained coarse textured lower horizons

To efficiently manage new forests throughout the British Columbia coastal zone, it is essential that herbicide treatment occur as close as possible to streams without jeopardizing critical riparian vegetation or endangering aquatic organisms. Floodplain areas often contain the best forest land and problems with competing brush species. Government agencies have attempted to protect riparian resources by establishing a 10-m pesticide free zone (PFZ) with appropriate buffers considered by environmental regulators to be essential to ensure that chemical trespass of this zone does not occur. Registration of ROUNDUP raised several regulatory concerns with regard to this issue: (1) could the PFZ be maintained along visible streams during aerial spraying, (2) what size buffer would prevent chemical trespass of the PFZ, and (3) what environmental and biological consequences might result from accidental overspray of streams not visible from the air because of extensive vegetative overgrowth?

To more fully address these concerns, a ROUNDUP environmental fate/impact study was designed for the Carnation Creek experimental watershed (Reynolds et al. 1989a) that would:

(1) provide a 10-m PFZ without an additional buffer along the main creek (visible), but

(2) allow for an overspray of certain floodplain tributaries (not visible) used as overwintering habitat by coho salmon.

The Carnation Creek glyphosate study was not designed as a silvicultural study, but silvicultural performance of the herbicide does have a bearing on the magnitude of environmental impact. The justification for herbicide use is that the treatment must work. Crop trees released by glyphosate from brush competition should survive and grow better than those not released.

To achieve the maximal environmental impact of ROUNDUP treatment at Carnation Creek, the maximum label rate (2.1 kg a.i./ha) was used, and the herbicide application was timed to achieve maximal residue inputs (autumn storms) when coho salmon would be most likely to come into contact with these residues (i.e., entry into oversprayed tributaries). Minimum impact on the crop trees was also anticipated at this time.

A MICROFOIL BOOM[1] was used because this aerial delivery technology could provide a 10-m PFZ without an additional buffer zone. The MICROFOIL BOOM emits very large spray droplets, which fall like rain drops to the ground and create a knife-edge effect between target and non-target vegetation. The three research protocols that were key to understanding the experiment were:

(1) maintenance of a 10-m vegetation buffer on either side of Carnation Creek;

(2) overspray of two tributaries designated as 750 and 1600; and

(3) a third tributary, designated as 2600, was an untreated control for 1600 and 750 (2600 was upstream of the treated portion of Carnation Creek watershed).

The tributary numbers correspond to the distance (m) from the estuary to its confluence with Carnation Creek, and indicate the length of floodplain sprayed above B-weir (500 m, the main flow guaging weir and stream sampling site). The treated floodplain was 80 to 270 m wide, and the total area treated above B-weir was 32.7 ha or 3.4% of the watershed. The two oversprayed tributaries differed substantially in their stream dynamics, and hence in their potential to act as environmental sinks for retaining herbicide residues. Tributary 750 is a short (50 m) valley-floor tributary characterized by rapid flow and flushing along a relatively straight reach of stream. By contrast, 1600 is a longer (250 m), slow-flowing, and slow-flushing tributary that meanders along the valley floor.

---

[1] Registered Trademark of Union Carbide, Inc., Ambler, Pa.

The Carnation Creek watershed was aerially treated with ROUNDUP between September 6 and 15, 1984 by Rotor Vegetation Control and Alpine Helicopters of Calgary (Reynolds et al. 1989a). Following treatment, environmental fate monitoring continued for one year and coincided with major winter storm events (Feng et al. 1989; Feng and Thompson 1989). Environmental impact and biological response research continued for up to three years post-treatment (Holtby 1989; Holtby and Baillie 1989a,b,c; Preston and Trofymow 1989; Reynolds et al. 1989b; Scrivener 1989; and Scrivener and Carruthers 1989). Weather conditions after treatment provided opportunities for measuring maximal redistribution of the herbicide in the environment (Hetherington 1989).

At Carnation Creek, ~75% of annual precipitation (Table 1) occurs during autumn and winter storm events (Hetherington 1982). The first sizable fall storm took place within 24 h of the completion of spraying. During autumn storms, many coho salmon moved out of the main channel to overwinter in tributaries such as 750, 1600 and 2600 until the beginning of spring when they again returned to the main channel (Tschaplinski and Hartman 1982). Fish moved into the tributaries to avoid the excessive turbulence of the mainstream during the winter. However, this movement placed the coho in direct exposure to glyphosate residues entering the tributaries as a result of autumn or winter storm events.

The Carnation Creek study provided several unprecedented opportunities to examine various aspects of fate, impact or biological response not addressed in prior research. Key among these opportunities were:

(1) the long-term salmonid data base for Carnation Creek (since 1970) is the most complete in North America,

(2) the concurrent coupling of the fisheries data base with environmental fate and impact research,

(3) a first-time ever examination of long-term watershed residue inputs from winter storm events and observations of long-term fish toxicity or avoidance resulting from these inputs, and

(4) a first-time ever examination of habitat changes induced by herbicide treatment, and the effects of these on fish populations and other aquatic organisms.

Toxicity, fate of residues, and biological responses of the resident fish population have been examined in other watersheds, but only in the short term. The impact on aquatic organisms of herbicide-induced habitat changes have not been addressed by these previous studies.

## RESULTS AND CONCLUSIONS

A few silvicultural results and conclusions are stated first as a foundation for conclusions from individual studies. Specific conclusions are preceded by the specific study objectives that were outlined in the introductory article (Reynolds et al. 1989a).

**Silvicultural conclusions** are as follows:

1. Formulation, tank mix, and deposit collector analyses indicated an accurate chemical application (Feng et al. 1989).

2. Herbicide efficacy was species dependent, but generally high for species that glyphosate is known to be effective against (Reynolds et al. 1989b).

3. Control of all noncommercial species declined 2 and 3 years after treatment (Reynolds et al. 1989b). This finding is consistent with other major glyphosate studies conducted on a global basis (Lund-Hoie and Gronvold 1987). There is no evidence that herbicide efficacy was reduced as a result of using the MICROFOIL BOOM.

4. Crop tolerance was species dependent with only minor injury to western redcedar and western hemlock and no injury to Sitka spruce (Reynolds et al. 1989b).
   - full recovery 1 year after treatment;
   - no cases of crop mortality;
   - no cases of stem deformity

5. Sitka spruce released by glyphosate treatment had a 40% advantage in diameter and a 63% advantage in diameter-increment over untreated trees 3 yrs after treatment (Reynolds et al. 1989b). Western hemlock growth also improved significantly, but data from western redcedar was too limited to show any growth enhancement from release.

6. Considering the late timing and the advanced state of the competition, ROUNDUP performed well silviculturally (Reynolds et al. 1989b).

### Conclusions of Individual Studies

**Objective 1**: Monitoring off-target glyphosate deposit.

**Conclusions**:

a. No residues were observed in buffered streams (Feng et al. 1989).

b. Under the specific conditions of this study, the 10-m vegetation buffer adequately protected streams from chemical contamination (Feng et al. 1989). Results reported by Payne et al. (1989) lend support to these findings.

**Objective 2**: Monitoring short-term glyphosate residues in oversprayed tributaries and those entering Carnation Creek from these tributaries.

**Conclusions**:

a. Highest residues in streamwater of a directly sprayed tributary (162 μg/L) were 50-fold below the lowest accepted 96 h $LC_{50}$ dose (7800 μg/L) for rainbow trout (Feng et al. 1989 and Servizi et al. 1987).

b. Residues declined to non-detectable levels within 96 h post-application (Feng et al. 1989).

**Objective 3**: Monitoring short-term, immediate effects of aerial ROUNDUP application on salmon fry behavior, movements, and mortality in relation to measured glyphosate residue levels in flowing tributaries and isolated pools in the experimental area.

**Conclusions**:

a. No fish mortality occurred that was attributable to the herbicide application (Holtby and Baillie 1989a).
   - mortality of caged fish appears to have been caused by storm injury;
   - there was no unusual mortality of resident coho at the time of spraying.

b. Caged coho showed signs of stress within 2 h of the application (Holtby and Baillie 1989a). Stress was minor and temporary.

c. Resident coho were caught less frequently in baited minnow traps and they appeared to avoid the fence on the oversprayed tributary (1600) for 3 wks after herbicide treatment (Holtby and Baillie 1989a).

Coho avoidance of minnow traps was accompanied by an increased movement of *Paraleptophlebia* (an aquatic mayfly) within 24 h after overspray (Kreutzweiser and Kingsbury 1989). This also indicated that stress observed for caged coho may have been caused by ROUNDUP. Field observations of coho stress are not in agreement with laboratory toxicity studies with ROUNDUP (Chapman 1989) reported elsewhere in this proceedings. In addition, residues were not measured where caged fish were held, but only where the tributary joins Carnation Creek. Residues may have been diluted as compared with elsewhere within the tributary, because canopy overgrowth of 1600 varied greatly from the lower to the upper reach of the tributary (Holtby and Baillie 1989a). Values observed at the mouth of 1600 may underestimate herbicide exposure. Vegetation shielding appeared to cause variation of glyphosate concentrated in natural and artificial ponds (range = 20 to 376 μg/L) immediately after overspray with ROUNDUP in northern Manitoba (Beck 1987). Holtby and Baillie (1989a) have also suggested that laboratory results are probably not applicable to the natural habitat where fish are actively seeking winter refuge soon after herbicide treatment. Fish entering a new environment would be more predisposed to the additional stress of being exposed to ROUNDUP.

**Objective 4**: Monitoring short-term aquatic invertebrate drift resulting from ROUNDUP exposure.

**Conclusions**:

a. Aquatic drift rates (downstream movement) of *Paraleptophlebia* mayflies and *Gammarus* amphipods doubled within 24 h after direct overspray (Kreutzweiser and Kingsbury 1989).
   - avoidance was short-lived;
   - *Paraleptophlebia* and *Gammarus* are especially sensitive species, and they might be useful indicator species for aquatic invertebrate drift induced by pollutants (Williams and Moore 1982; Muirhead-Thomson 1985);
   - drift rates did not increase for any other invertebrate species.

**Objective 5**: Monitoring the movement of glyphosate residues into side channels following major autumn and winter storm events.

Seven major storms with peak flows from 7.7 to 28 $m^3/s$ occurred from 23 to 150 days post-application.

**Conclusions**

a. Trace levels in streamwater of oversprayed tributaries (1600 and 750) were associated with these storm events (Feng et al. 1989). No detectable residues were found in buffered tributaries (C creek and 1450) during this monitoring period, indicating that the PFZ effectively prevented stream contamination from both off-target deposit and subsequent inputs (Feng et al. 1989).

b. The highest residues were observed in tributary bottom sediments, which are the major sink for this compound (Feng et al. 1989).

c. Glyphosate was found in bottom sediments throughout the 150-d period in one treated tributary (1600); but it was observed only sporadically in the other tributary (750) during this period (Feng et al. 1989). Differences in glyphosate accumulation for the two tributaries are the result of differences in stream dynamics and flushing for the two tributaries.

d. Sediment residues were not biologically active because they remained bonded to the sediments (Feng et al. 1989).

**Objective 6**: Measuring the persistence and dissipation of glyphosate in riparian foliage and soils.

Red alder and salmonberry are the major riparian vegetation growing along tributary streambanks at Carnation Creek and elsewhere within the British Columbia coastal forest. Both species are the major brush competitors at Carnation Creek, and are two of four major brush competitors throughout the coastal area. Ironically, both species are key components of the physical habitat (stability, cover) and of the aquatic food web sustaining coho salmon. Hence, regulators have expressed concern that glyphosate residues deposited on target vegetation, especially alder or salmonberry, not serve as a possible source of toxic contamination for aquatic organisms that use their leaf-litter in the aquatic food web.

**Conclusions**:

Foliage

a. High deposition of glyphosate occurred on target brush species (Feng and Thompson 1989).

b. Foliage residue levels declined significantly within 15 d after ROUNDUP treatment and continued to decline progressively over time (Feng and Thompson 1989).
   - less than 1% remained 29 days post-application:
   - less than 0.1% remained 75 days post-application:

c. Results showed that residue levels in leaf-litter of major brush species presented an insignificant, transient source of chemical input onto forest floor or into streams.

Soils

a. Soil residues of both glyphosate and its metabolite, AMPA, declined over time in both seasonally flooded and well-drained soils (Feng and Thompson 1989).
   - estimated glyphosate half-life ($DT_{50}$) is 45 to 60 days:
   - only 6 to 18% of initial levels remained after 360 days:

Floodplain soils varied in their degree of soil saturation throughout the year. Drainage of these soils at Carnation Creek has been described by Hetherington (1989). Chemical decomposition rates varied depending on soil saturation levels (Feng and Thompson 1989). For well-drained soils, more aerobic conditions existed for longer periods throughout the year, and more rapid microbial decomposition of chemical residues was expected. For seasonally flooded soils, anaerobic conditions existed over longer periods, and slower microbial decomposition of chemical residues was expected. Declining glyphosate residues coupled with transient increases in metabolite residues were indicative of microbial degradation. The latter conclusion is in agreement with results reported by Preston and Trofymow (1989). They also found no toxic effects of soil glyphosate and metabolite residues on soil microbes or macrofauna. No changes in soil microbe populations or in soil denitrification were observed as a consequence of herbicide treatment.

b. The Carnation Creek study provided no evidence of extraordinary soil persistence of either glyphosate or its metabolite (Feng and Thompson 1989).

Results at Carnation Creek are in agreement with those reported by Newton et al. (1984) for a semi-arid Oregon forest watershed study.

c. Limited leaching potential was observed for both soil types (Feng and Thompson 1989).
- most of the residues (90%) were usually associated with the top 5-cm organic layer;
- no quantifiable residues were detected in samples taken from the 30-35 cm layer.

Hydrologic studies for the Carnation Creek watershed suggest that any mobile residues would leach vertically until the water table was reached, then tend to move laterally once the water table or surface water was encountered (Hetherington 1989). For seasonally flooded soils, the water table generally occurred near or at the surface for several months each year. Throughout the observation period, residues were lowest at the seasonally-flooded site; it is probable that reduced levels could be attributed to movement of chemical away from the sampling site by surface water, with residues either in solution or on transported fine sediment (Feng and Thompson 1989).

d. The limited mobility exhibited by glyphosate in Carnation Creek soils is due to strong adsorption to cation saturated clays and/or organic matter in the upper soil horizons (Feng and Thompson 1989).

Glyphosate binding to soils is positively correlated with clay content, cation exchange capacity and unoccupied phosphate adsorption capacity (Hance 1976; Hensley et al. 1978; and Sprankle et al. 1975). Carnation Creek soils are characterized by a relatively high cation-exchange capacity and organic matter content, especially in the upper 15 cm layers.

e. The data provides no evidence of potential for long-term groundwater or surface water contamination as a result of inputs from terrestrial substrates (Feng and Thompson 1989).

**Objective 7**: Assessing habitat changes induced by glyphosate treatment (water temperature, changes in riparian vegetation, erosion, sediment inputs, stream chemistry, algal populations, aquatic and terrestrial invertebrate fish-food, litter inputs, etc.) in the main stream and treated tributaries.

**Conclusions**:

a. Litter-fall for tributary 1600 was reduced to 6% of expected deposition in 1985, the year after overspray (Holtby and Baillie 1989b), without apparent measurable biological impact.

Reduction was short-lived, with rapid progressive recovery 2-3 yrs post-application. Herbicide efficacy progressively declined in year two and three after treatment (Reynolds et al. 1989b). Alder and salmonberry rapidly resprouted, reversing environmental changes induced by defoliation, including reduced stream litter inputs in 1985. Other environmental changes induced by herbicide defoliation of alder and salmonberry included: (a) increased sunlight reaching the stream surface, (b) warmer stream temperatures, (c) increased erosion, and (d) increased nutrient inputs. These changes occurred for 1 or 2 yrs and they were accompanied by biological responses which were either beneficial, neutral or detrimental.

b. Streamwater temperature increased in 1600 in 1985 resulting from defoliation of riparian alder (Holtby 1989).

- temperatures decreased to pre-treatment levels within 3 yrs;
- no adverse effects of temperature increase on resident salmonids in 1600;
- increased temperatures probably contributed to increased algal production in the year after treatment (Holtby and Baillie 1989c and Scrivener 1989).

c. Streamwater conductivity increased 21% during freshets in the year following herbicide treatment (Scrivener 1989).
  - increases were due to enhanced leaching of ions;
  - increases were short-lived (1-2 yrs);
  - increases had no apparent biological impact.

d. Streamwater nitrate ($NO_3$) levels for 1600 increased 3-fold during freshets in the year following herbicide treatment (Scrivener 1989).
  - increases resulted from release of $NO_3$ from roots of dead vegetation;
  - increases were short-lived;
  - streamwater concentrations did not reach levels that were known to be toxic to salmonid eggs; there were no adverse biological impacts observed.

These results are in agreement with those reported by Kimmins et al. (1989) for another coastal British Columbia watershed.

e. Streamwater phosphate ($PO_4$) concentration increased after herbicide treatment (Scrivener 1989).
  - increases resulted primarily from deciduous litter inputs;
  - similar increases were not observed after logging and slash-burning; after herbicide treatment, $PO_4$ was released from herbicide-treated brush (litter from treated brush was not destroyed by slash-burning and had a much higher $PO_4$ content than coniferous logging slash);
  - increases were short-lived (1-2 yrs);
  - increased algal production (10 to 100-fold) occurred in the year after herbicide treatment due to increased levels of $PO_4$ and light (Holtby and Baillie 1989b);
  - increased algal production was short-lived;
  - phosphorus was the primary factor limiting algal production in Carnation Creek (Stockner and Shortreed 1978).

Enhanced algal production may have off-set, to some degree, any food losses that may have resulted from the temporary interruption in stream litter inputs.

f. Herbicide overspray of 1600 had no measurable direct effects on invertebrate abundance or community composition during the post-spray monitoring period, but densities declined in conjunction with streamflow, a primary limiting factor (Scrivener and Carruthers 1989).
  - densities of aquatic fish-food organisms were inversely related to mean streamflow during the 60-d period prior to the date of sampling;
  - invertebrate abundance was similar at treated and untreated sites during most streamflows, but after periods of frequent freshets invertebrate abundance was 40-50% lower at sites that were treated with ROUNDUP (Scrivener and Carruthers 1989);
  - high water velocities accompanied by the movement of fine sediments along the streambed were probably responsible for any loss of fish-food organisms (Culp and Davies 1983).

The presence of ponded water in the tributaries during the ROUNDUP application (Hetherington 1989) probably protected the aquatic plants from any damage. This aquatic rooted vegetation would be damaged if the sites had been dry because it is susceptible to ROUNDUP (Grossbard and Atkinson 1985). Aquatic invertebrates would have been impacted further because their densities at bare mud sites were 10-25% of those at sites with aquatic rooted vegetation in 750, 1500 and 1600 tributaries (Scrivener and Caruthers 1989).

**Objective 8**: Monitoring fish use of side channels in the long-term following glyphosate application relative to habitat changes or relative to residues in water and stream sediment.

**Conclusions**:

a. There were no differences in pre-treatment and post-treatment use of oversprayed streams by overwintering coho (Holtby and Baillie 1989a).

b. Post-treatment mortality, growth rates, and spring emigration during 1985 and 1986 did not differ for overwintering coho as compared with pre-treatment years (Holtby and Baillie 1989a).

## SUMMARY CONCLUSIONS

Several regulatory concerns about the use of ROUNDUP were discussed in the Introductory Remarks. Briefly, these were:

(1) Concerns that coastal British Columbia forest environmental conditions are dissimilar to previously studied forest ecosystems in the Pacific northwest. (This difference might produce substantially differing results with regard to the environmental fate/impact of ROUNDUP following aerial application, and as a consequence, elicit undesirable biological responses from non-target organisms.);

(2) Concerns about toxicity of the surfactant used in the ROUNDUP formulation to salmonids. (The surfactant might be more toxic to aquatic organisms than the active ingredient of ROUNDUP - glyphosate.);

(3) Concerns that provincial and federal governement policy requiring a 10-m pesticide free zone (PFZ) with appropriate buffers to protect riparian resources was burdensome, or might not be adequate to protect against undesirable ROUNDUP trespass. (Is the current PFZ of 10-m adequate and what, if any, additional buffers are needed to protect the integrity of the PFZ?);

(4) Concerns about the environmental and biological consequences that might result from overspray of streams not visible from the air. (Even if the PFZ is adequate to protect visible streams, undesirable environmental impacts and biological responses might result from overspray of nonvisible streams).

### Similarity of Carnation Creek to Other Ecosystems

Short-term ROUNDUP environmental fate results at Carnation Creek are in agreement with those reported for a semi-arid Oregon forest watershed study (Newton et al. 1984), and for a Manitoba study (Beck 1987). Monitoring of residues lasted for 55 days and 30 days post-application in the Oregon and Manitoba studies, respectively as compared with one year for this study. Results of both studies provided no basis for concern. Coho salmon fingerlings did not accumulate detectable amounts of glyphosate or metabolite residues in the Oregon study. However, direct toxicity and behavioral responses of coho salmon to ROUNDUP stress were not monitored in the Oregon study. Fish were not present in the Manitoba ponds. To date, the Carnation Creek herbicide study is the most complete and exhaustive ecosystem study with ROUNDUP and coho. There are no other studies with which all aspects of the Carnation Creek research can be compared.

## Surfactant Toxicity

No fish mortality occurred at Carnation Creek that was attributed to the herbicide and no juvenile coho avoidance was observed in streams with a vegetation buffer following ROUNDUP application (Holtby and Baillie 1989a). However, resident coho salmon appeared to avoid entering tributary 1600 and baited traps in tributary 1600 for 3 wks after herbicide treatment. Holtby and Baillie (1989a, c) suggested that the surfactant in the ROUNDUP formulation, not the active ingredient (glyphosate), may have been responsible for inducing temporary stress in caged and resident coho fry and for decreasing algal production in the overpsrayed tributary during the first 2 wks after application. The surfactant is known to be at least 4 times more toxic than glyphosate, although its concentration in the tributary could never have been more than 1/25 of concentrations that caused 50% mortalities within 96 h (ROUNDUP formulation = 30.5% glyphosate, 15% surfactant; Servizi et al. 1987; Feng et al. 1989 and Folmar et al. 1979). Surfactant residues were not measured directly during the present study, therefore future research on surfactant toxicity may be worthwhile. The temporary stress that was observed among aquatic organisms justifies present procedures for ROUNDUP use without additional restrictions.

## Value and Adequacy of PFZ

The value of a PFZ, or adequate buffers to protect it, is to prevent toxic chemicals from entering streams and to prevent damage to riparian vegetation. Protection of riparian vegetation is of greater concern than aquatic toxicity when ROUNDUP is used. Streamside trees and brush, and logs in the stream reduce erosion of the banks and channel, and provide the riffles, pools and cover that are essential to resident fish (Hartman et al. 1987). Stream channels straighten, shallow and widen over time in order to transport water during freshets unless large trees and brush remain on the stream banks.

At Carnation Creek, a MICROFOIL BOOM was used because this aerial delivery technology should have maintained a 10-m PFZ without an additional buffer zone. This assumption was proven correct since riparian vegetation was unaffected and no residues were observed in streams with a PFZ (Feng et al. 1989). The large droplets, slow speed (40 km/h) and low elevation (6-18 m) permitted maximum control (Reynolds et al. 1989a) of a low toxicity herbicide. The MICROFOIL BOOM has rarely been used operationally in British Columbia.

The use of more toxic, less bio-degradable or less chemically bonding herbicides that are applied with less control (smaller droplets, fixed-wing aircraft) require greater protection of the riparian zone. In British Columbia, conventional boom and nozzle equipment (e.g., D8-46) is more commonly used operationally. An additional buffer was recommended for the 10-m PFZ when ROUNDUP was applied with a Thru-Valve Boom (TVB[2]) or with D8-46 hydraulic nozzles (Payne et al. 1989). Acute toxicity studies have shown herbicides such as GARLON 4 to be 14 times more toxic to salmonids (96 h - $LC_{50}$) than ROUNDUP (Servizi et al. 1987). All workshop discussion groups, tasked with evaluating the PFZ concept, concluded that the PFZ is both desirable and adequate as currently enforced to protect coastal riparian resources in British Columbia (e.g., discussion groups 11 and 12, this proceedings).

---

[2] Registered Trademark of Waldrum Specialties, Inc., Ambler, Pa.

### Overspray

Results of the present research confirm that no short-term (96 h) toxicity was observed for fish or other aquatic organisms that could be attributed to glyphosate or metabolite residues in oversprayed tributaries. Short-term stress was observed for fish, algae and two invertebrates for up to 3 wks following overspray of tributary 1600. The present research found no evidence of long-term environmental consequences resulting from overspray, since rapid refoliation of treated vegetation occurred within 3 yrs of ROUNDUP application (Reynolds et al. 1989b). Little erosion potential was evident in the oversprayed tributaries that would necessitate a 10-m PFZ. The beds of all these treated tributaries consisted of mud with rooted aquatic plants instead of coarser materials (e.g. gravel) that were evident in streams transporting significant amounts of sediment. However, it was evident that if the aquatic rooted vegetation had been killed by the herbicide, aquatic invertebrates would have been affected (Scrivener and Carruthers 1989). Most of these aquatic plants were covered by ponded water that prevented direct contact by the spray at the time of herbicide application.

All workshop discussion groups that attempted to evaluate the PFZ concept were unable to determine just how much riparian habitat destruction can be tolerated before unacceptable or irreversible ecosystem damage might result. Until this can be better determined, all groups felt that existing provincial PFZ guidelines should not be relaxed. The size of PFZ and buffers necessary will depend on the herbicide and the application method used. The regulatory system must be flexible enough to accommodate this reality.

To conclude, the present research demonstrates that glyphosate can be used operationally within the British Columbia coastal forest zone without posing an unacceptable impact on salmonids provided current label and regulatory guidelines are strictly observed.

## LITERATURE CITED

Beck, A.E. 1987. Persistence of glyphosate residues in northern Manitoba ponds. Water standards and studies Rep. 87-2. Environmental Management Division, Manitoba Department of Environment and Workplace Safety and Health. Winnipeg, Manitoba. 41 p.

Chapman, P.M. 1989. Salmonid toxicity studies with ROUNDUP. This proceedings.

Culp, J.M. and R.W. Davies. 1983. An assessment of streambank clearcutting on macroinvertebrate communities in a managed watershed. Can. Tech. Rep. Fish. Aquat. Sci. 1208:116 p.

Feng, J.C. and D.G. Thompson. 1989. Persistence and dissipation of glyphosate in foliage and soils of a Canadian coastal forest watershed. This proceedings.

Feng, J.C., D.G. Thompson and P.E. Reynolds. 1989. Fate of glyphosate in a Canadian forest stream ecosystem. This proceedings.

Folmar L.C., H.O. Sanders and A.M. Julin. 1979. Toxicity of the herbicide glyphosate and several of its formulations to fish and aquatic invertebtates. Arch. Env. Conta Toxicol. 8:269-278.

Grossbard, E. and D. Atkinson (Eds.). 1985. The herbicide glyphosate. Buttersworth Ltd., London, U.K. 263 p.

Hance, R.J. 1976. Adsorption of glyphosate by soils. Pestic. Sci. 7: 363-366.

Hartman, G.F., J.C. Scrivener, L.B. Holtby and L. Powell. 1987. Some effects of different streamside treatments on physical conditions and fish population processes in Carnation Creek, a coastal rain-forest stream in British Columbia, p. 338-370 In: E.O. Salo and T.W. Cundy (Eds.). Streamside Management - forestry and fishery interactions. Contribution No. 57, Institute of Forest Resources, AR-10, University of Washington, Seattle, WA 98195.

Hensley, D.L., D.S.N. Beuerman, and P.L. Carpenter. 1978. The inactivation of glyphosate by various soils and metal salts. Weed Res. 18: 287-291.

Hetherington, E. 1982. A first look at logging effects on the hydrologic regime of Carnation Creek experimental watershed, p. 45-62. In G.F. Hartman (Ed.) Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station. Nanaimo. British Columbia. 404 p.

Hetherington, E. 1989. Carnation Creek floodplain hydrology September 1984 to September 1985. This proceedings.

Holtby, L.B. 1989. Changes in the temperature regime of a valley-bottom tributary of Carnation Creek, British Columbia, over-sprayed with herbicide ROUNDUP (glyphosate). This proceedings.

Holtby, L.B. and S.G. Baillie. 1989a. Effects of the herbicide ROUNDUP on coho salmon fingerlings in an over-sprayed tributary of Carnation Creek, British Columbia. This proceedings.

Holtby, L.B. and S.G. Baillie. 1989b. Litter-fall and detrital decomposition rates in a tributary of Carnation Creek, British Columbia, over-sprayed with the herbicide ROUNDUP (glyphosate). This proceedings.

Holtby, L.B. and S.G. Baillie. 1989c. Effects of the herbicide ROUNDUP (glyphosate) on periphyton in Carnation Creek, British Columbia. This proceedings.

Kimmins, G.P., K.M. Tsze and R.E. Bigley. 1989. Development of non-commercial vegetation following clearcutting and clearcutting-plus-slashburning, and some biogeochemical effects of herbicidal control of this vegetation. This proceedings.

Kreutzweiser, D.P. and P.D. Kingsbury. 1989. Drift of aquatic invertebrates in a glyphosate contaminated watershed. This proceedings.

Lund-Hoie, K. and S. Gronvold. 1987. Glyphosate application in forest - ecological aspects. I. Successional vegetation changes. Scand. J. For. Res. 2:455-468.

Muirhead-Thomson, R.C. 1985. Pesticide impact on stream fauna with special reference to macroinvertebrates. Cambridge University Press. Cambridge, U.K.

Newton, M., K.M. Howard, B.R. Kelpas, R. Danhaus, C.M. Lottman, and S. Dubleman. 1984. Fate of glyphosate in an Oregon forest ecosystem. J. Agric. Food Chem. 32:1144-1151.

Payne, N., J. Feng and P.E. Reynolds. 1989. Off-target deposit measurements and buffer zones required around water for various aerial applications of glyphosate. This proceedings.

Preston, C.M. and J.A. Trofymow. 1989. Effect of glyphosate on biological activity of two forest soils. This proceedings.

Reynolds, P.E., J.C. Scrivener, L.B. Holtby and P.D. Kingsbury. 1989a. Overview of Carnation Creek herbicide project: historical perspective, experimental protocols, spray operations. This proceedings.

Reynolds, P.E., D.G. Pitt, R. Whitehead and K. King. 1989b. Three-year herbicide efficacy, crop tolerance and crop growth response results for a 1984 glyphosate conifer release trial at Carnation Creek, British Columbia. This proceedings.

Scrivener, J.C. 1989. Changes in concentration of dissolved ions following herbicide application (glyphosate) at Carnation Creek, British Columbia. This proceedings.

Scrivener, J.C. and S. Carruthers. 1989. Changes in the invertebrate populations of the main stream and back channels over-sprayed with herbicide at Carnation Creek, British Columbia. This proceedings.

Servizi, J.A., R.W. Gordon and D.W. Martens. 1987. Acute toxicity of Garlon 4 and Roundup herbicides to salmon, *Daphnia*, and trout. Bull. Environ. Contam. Toxicol. 39:15-22.

Sprankle, P., W.F. Meggitt and D. Penner. 1975. Adsorption, mobility and microbial degradation of glyphosate in the soil. Weed Sci. 23:229-234.

Stockner, J.G. and K.S. Shortreed. 1978. Enhancement of autotrophic production by nutrient addition in a coastal rainforest stream on Vancouver Island. J. Fish. Res. Board Can. 35:28-34.

Tschaplinski, P.J. and G.F. Hartman. 1982. Winter distribution of juvenile coho salmon (*Oncorhyndrus kisitch*) in Carnation Creek and some implications to overwinter survival, p. 273-286. In: G.F. Hartman (Ed.) Proceedings of the Carnation Creek Workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia. 404 p.

Williams, D.D. and K.A. Moore. 1982. The effect of environmental factors on the activity of *Gammarus pseudolimnaeus* (Amphipoda). Hydrobiologia 96:137-147.

## Symposium Attendees

Peter Ackhurst
Min. of Forests & Lands
4th Floor
4595 Canada Way
Burnaby, B.C.
V5G 4L9

Rob Adams
Min. of Envir. & Parks
810 Blanshard St.
Victoria, B.C.
V8V 1X5

Harold Armleder
Min. of Forests & Lands
540 Borlund St.
Williams Lake, B.C.
V2G 1R8

Mark Atherton
Pacific Forestry Centre
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

T.E. Baker
Research Branch
Min. of Forests & Lands
31 Bastion Sq.
Victoria, B.C.
V8W 3E7

Steve Baillie
Fisheries & Oceans
Hammond Bay Rd.
Nanaimo, B.C.
V9R 5K6

Patty Balfour
Min. of Environment & Parks
780 Blanshard St.
Victoria, B.C.
V8V 1X5

Bryce Bancroft
4712 Eastridge Rd.
North Vancouver, B.C.
V7G 1K4

Kathy Banky
1030 Princess Ave.
Victoria, B.C.
V8T 1L1

Larry J. Barr
Min. of Envir. & Parks
810 Blanshard St.
Victoria, B.C.
V8V 1X5

John Bartlett
4075 Tyndall Ave.
Victoria, B.C.
V8N 3R7

Ernie Beadle
Min. of Forests & Lands
4226 6th Ave.
Port Alberni, B.C.
V9Y 4N1

Bill Beard
Min. of Forests & Lands
Box 470
Revelstoke, B.C.
V0E 2S0

Pierre Beaudry
Min. of Forests & Lands
Bag 5000
Smithers, B.C.
V8J 2N0

Rod Beaumont
Weldwood of Canada
Box 2179
Vancouver, B.C.
V6B 3V8

Henry Benskin
Min. of Forests & Lands
31 Bastion Sq.
Victoria, B.C.
V8W 3E7

Al Blattler
Whonnock Ind. Ltd.
Box 49114
1055 Dunsmuir St.
Vancouver, B.C.
V7X 1H7

Jacob Boateng
Min. of Forests & Lands
31 Bastion Sq.
Victoria, B.C.
V8W 3E7

Bill Bourgeois
MacMillan Bloedel Ltd.
65 Front St.
Nanaimo, B.C.
V9R 5H9

Shane Bowden
Min. of Forests & Lands
Box 1939
Revelstoke, B.C.
V0E 2S0

Dr. David Bowering
Min. of Health
3412 Kalum St.
Terrace, B.C.
V8G 4T2

Tom Brown
Fisheries & Oceans
Hammond Bay Rd.
Nanaimo, B.C.
V9R 5K6

Peter Bruce
MacMillan Bloedel Ltd.
65 Front St.
Nanaimo, B.C.
V9R 5H9

Gordon Burton
B.C. Forest Prod. Ltd.
Box 130
Crofton, B.C.
V0R 1R0

Dick Cain
B.C. Forest Prod. Ltd.
#311-1180 Ironwood Rd.
Campbell River, B.C.
V9W 5P7

Norm Caldicott
Min. of Forests & Lands
Box 1970
Squamish, B.C.
V0N 3G0

Errol Caldwell
Forest Pest Management Inst.
Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Robert A. Campbell
Pest Control Section
Min. of Natural Resources
Maple, Ont.
L0J 1E0

Glen Carlson
Min. of Environ. & Parks
10334-152 A St.
Surrey, B.C.
V3R 7P8

Les Carlson
Canadian Forestry Service
Place Vincent Massey
351 St. Joseph Blvd.
Hull, P.Q.
K1A 1G5

Bob Cerenzia
Fisheries & Oceans
4515 Elizabeth St.
Port Alberni, B.C.
V9Y 6L5

Tom Chamberlain
Habitat Protection
780 Blanshard St.
Victoria, B.C.
V8V 1X5

Blythe Chang
Fisheries & Oceans
80-6th St. Room 330
New Westminster, B.C.
V3L 5B3

Bernie Chapman
MacMillan Bloedel Ltd.
Box 630
Chemainus, B.C.
V0R 1K0

Phil Comeau
Faculty of Forestry
UBC
270-2357 Main Mall
Vancouver, B.C.
V6T 1W5

Miles Constable
Environment Canada
4999-98th Ave. Room 210
Edmonton, Alta.
T6B 2X3

Wayne Coombs
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Pete Corbett
Box 1313
Golden, B.C.
V0A 1H0

Allan Cowan
Fisheries & Oceans
Box 99
Queen Charlotte City, B.C.
V0T 1S0

John Cowell
Monsanto Agricultural Co.
700 Chesterfield Village Pkwy BB5K
St. Louis, Missouri
U.S.A. 63198

Susan Craven
Crown Forest Prod.
Box 470
Sandspit, B.C.
V0T 1T0

Ron Craig
Vancouver Water Resources
4330 Kingsway
Burnaby, B.C.
V5H 4G8

Dan Cronin
Min. of Environment & Parks
Pesticide Control
780 Blanshard St.
Victoria, B.C.
V8V 1X5

Brian Dane
Fisheries & Oceans
80-6th St.
New Westminster, B.C.
V3L 5B3

Brian D'Anjou
Min. of Forests & Lands
4595 Canada Way
Burnaby, B.C.
V5G 4L9

Michel de Bellefeuille
MacMillan Bloedel Ltd.
Juskatla, B.C.
V0T 1J0

Jack de Lestard
Pacific Forestry Centre
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Bruce Devitt
CIP Inc.
Tahsis Pacific Region
1201 W. Pender St.
Vancouver, B.C.
V6E 2V4

Dave DeYoe
MacMillan Bloedel Ltd.
65 Front St.
Nanaimo, B.C.
V9R 5H9

W.R. Dinsmore
B.C. Hydro R&D
12388-88th Ave.
Surrey, B.C.
V3W 7R7

Bob Dobbs
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

G.F. Dodd
Min. of Forests & Lands
Box 828
Terrace, B.C.
V8G 4R1

Brian Downie
Min. of Forests & Lands
Bag 5000
Smithers, B.C.
V0J 2N0

Jack Dryburgh
MacMillan Bloedel Ltd.
3926 Compton Rd.
Port Alberni, B.C.
V9Y 6B5

Michelle Edwards
Regional Pesticide Officer
Agriculture Canada
#315, 80-6th St.
New Westminster, B.C.
V3L 5B3

Rick Ellis
2250 Arbutus Rd.
Victoria, B.C.
V8N 1V3

Basil English
Box 2006
Herald Ave.
Corner Brook, Nfld.
A2H 6J8

Arnold Erickson
Min. of Forests & Lands
845 Columbia St.
Castlegar, B.C.
V1N 1H3

Paul Erickson
Min. of Trans. & Hwys.
3D-940 Blanshard St.
Victoria, B.C.
V8W 3E6

Michael Feller
Faculty of Forestry
University of B.C.
Vancouver, B.C.
V6T 1W5

Joseph Feng
Northern Forestry Centre
5320-122nd St.
Edmonton, Alta
T6H 3S5

Gerry Fox
Min. of Environ. & Parks
310 Ward St.
Nelson, B.C.
V1L 5S4

Gerry Fraser
CIP Inc.
Tahsis Pacific Division
702 Memorial Ave.
Qualicum Beach, B.C.
V0R 2T0

Rick Gaudet
Monsanto Canada
55 Murray Pk. Rd.
Winnipeg, Manitoba
R3J 3W2

D.J. Girodat O.I.C.
3019-4th Ave.
Port Alberni, B.C.
V9Y 2B8

R.P. Gladiuk
Min. of Forests & Lands
9850 South McGrath Rd.
Box 159
Rosedale, B.C.
V0X 1X0

Dave Gluns
Min. of Forests & Lands
518 Lake St.
Nelson, B.C.
V1L 4C6

John Goette
Monsanto
800 N. Lindbergh Blvd.
St. Louis, Missouri
U.S.A. 63167

Phil Haddock
Federation of B.C. Naturalists
4620 West 2nd Ave.
Vancouver, B.C.
V6R 1L1

Stewart Hagen
Meadow Ridge Weed & Pest Control Ltd.
Maple Ridge, B.C.

Sue Hahn
Fisheries & Oceans
Box 10
Madeira Park, B.C.
V0N 2H0

Dave Haley
Pacific Forestry Centre
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Jim Hall
Domans
435 Trunk Rd.
Duncan, B.C.
V9L 2P9

J. Peter Hall
Canadian Forestry Service
Research & Technical Services
351 St. Joseph Blvd.
11th Floor, Place Vincent Massey
Hull, P.Q.
K1A 1G5

Mike Halleran
Box 1090
Kaslo, B.C.
V0G 1M0

Shawn Hamilton
Fisheries & Oceans
716 Fraser St.
Prince Rupert, B.C.
V8J 1P9

Dennis Hamilton
Min. of Environ. & Parks
426-14th St.
Box 233
Invermere, B.C.
V0A 1K0

Paul V. Hanna
Western Forest Prod. Ltd.
Holberg, B.C.
V0N 1Z0

Alton Harestad
Dept. Biological Studies
Simon Fraser University
Burnaby, B.C.
V5A 1S6

Rob Harder
MacMillan Bloedel Ltd.
Cameron Division
Port Alberni, B.C.
V9Y 7N4

Chris Hayhurst
Min. of Forests & Lands
2830-16th Ave.
Port Alberni, B.C.
V9Y 3A2

Winnifred Hays
FVA-Research
27-7925 Simpson Rd.
Victoria, B.C.
V0S 1M0

John Henigman
Protection Branch
Min. of Forests & Lands
31 Bastion Sq.
Victoria, B.C.
V8W 3E7

Eugene Hetherington
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V9Z 1M5

R.J. Higgins
Fisheries & Oceans
3225 Stephenson Pt. Rd.
Nanaimo, B.C.
V9T 1K3

Silvi Holmsen
201-2112 West Broadway
Vancouver, B.C.
V6K 2C8

L.B. Holtby
Fisheries & Oceans
Pacific Biological Station
Nanaimo, B.C.
V9R 5K6

Keith Illingworth
Research Branch
Min. of Forests & Lands
31 Bastion Sq.
Victoria, B.C.
V8W 3E7

Wayne Inkpen
Alberta Min. of Environ.
5th Floor
9820-106th St.
Edmonton, Alta.
T5K 2J6

Ted Jansen
Alpine Helicopters
165 George Craig Blvd. N.E.
Calgary, Alta.
T2E 7H3

Eric Jeklin
13660 Colebrook Rd.
Surrey, B.C.
V3S 4N7

Tom Johnston
Min. of Forests & Lands
845 Columbia Ave.
Castlegar, B.C.
V1N 1H3

Brian Jollymore
Fisheries & Oecans
Box 550
Halifax, N.S.
B3J 2S7

Bob Jones
Silvelec Services
4735 Carloss Place
Victoria, B.C.
V8Y 1C9

John Karakatsoulis
Faculty of Forestry
U.B.C.
270-2357 Main Mall
Vancouver, B.C.
V6T 1W5

Jerry Kennah
Min. of Forests & Lands
4595 Canada Way
Burnaby, B.C.
V5G 4L9

Hamish Kimmins
Faculty of Forestry
U.B.C.
270-2357 Main Mall
Vancouver, B.C.
V6T 1W5

Keith King
Pacific Forestry Centre
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Peter Kingsbury
Forest Pest Mgmt. Inst.
1219 Queen St. E.
Sault Ste. Marie, Ont.
P6A 5M7

Herb Klassen
V.A. Poulin & Assoc.
2153 W. 46th Ave.
Vancouver, B.C.
V6M 2L2

Dick Kosick
CIP Inc.
Tahsis Pacific Region
702 Memorial Ave.
Qualicum Beach, B.C.
V0R 2T0

Glenn Kostiuk
Fisheries & Oceans
Box 9
Alert Bay, B.C.
V0N 1A0

George Krumlik
Research Branch
Min. of Forests & Lands
31 Bastion Sq.
Victoria, B.C.
V8W 3E7

Rick Kussat
E.P.S.
Capilano 100 Park Royal
West Vancouver, B.C.
V7T 1A2

S.P. Lackey
Crown Forest Prod. Ltd.
Box 220
Campbell River, B.C.
V9W 5B1

John Lamb
Fisheries & Oceans
3225 Stephenson Pt. Rd.
Nanaimo, B.C.
V9T 1K3

Len Lanteigne
Forestry Canada - Maritimes
Box 4000
Fredericton, N.B.
E3B 5P7

Phil LePage
Min. of Forests & Lands
3726 Alfred St.
Bag 5000
Smithers, B.C.
V0J 2N0

Terry Lewis
6149 Burns St.
Burnaby, B.C.
V5H 1X3

Dave Lindsay
B.C. Forest Products Ltd.
Box 130
Crofton, B.C.
V0R 1R0

Gary Lloyd
Min. of Forests & Lands
Bag 5000
Smithers, B.C.
V0J 2N0

Jim Loftus
MacMillan Bloedel Ltd.
Box 160
Sayward, B.C.
V0P 1R0

Dan Lousier
Site 11 Box 102
R.R. #1
Lantzville, B.C.
V0R 2H0

Thomas Lundgren
Whonnock Industries Ltd.
Box 49114; Four Bentall Centre
105 Dunsmuir St.
Vancouver, B.C.
V7X 1H7

Bruce MacDonald
Fisheries & Oceans
2392 Ospika Blvd.
Prince George, B.C.
V2N 3N5

William Mack
Weldwood
#215-1180 Ironwood Rd.
Campbell River, B.C.
V9W 5P7

Roy Maki
Monsanto Canada
2330 Argentia Rd.
Box 787
Streetsville, Ont.
L5M 2G4

Joseph M. Malik
Monsanto Co. BB5F
700 Chesterfield Village Pkwy.
St. Louis, Missouri
U.S.A. 63198

John Manville
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Jean-Pierre Martel
Canadian Pulp & Paper Assoc.
Sun Life Bldg. 23rd Floor
1155 Metcalfe St.
Montreal, P.Q.
H3B 2X9

Bill Martin
Pace Chemicals
8321 Willard St.
Burnaby, B.C.
V3N 2X3

Laura Martin
MacMillan Bloedel Ltd.
301-4400 Marine Dr.
Powell River, B.C.
V8A 2K1

Ian McDougall
Min. of Environ. & Parks
2569 Kenworth Rd.
Nanaimo, B.C.
V9T 4P7

Kerry McGourlick
Western Forest Prod. Ltd.
Box 155
Holberg, B.C.
V0N 2Z0

Bill McJannet
Indian & Northern Affairs-Canada
Yukon Forest Service
Whitehorse, Yukon
Y1A 2B5

Wanda Michalowicz
Ontario Environment
64 McCallum Dr.
Richmond Hill, Ont.
L4C 7T5

Adrian Miller
Environmental Services
B.C. Hydro
1265 Howe St. 5th Floor
Vancouver, B.C.
V6Z 2C8

Gord Miller
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Rick Morley
Min. of Environment & Parks
780 Blanshard St.
Victoria, B.C.
V8V 1X5

Doug Morrison
Min. of Environ. & Parks
2569 Kenworth Rd.
Nanaimo, B.C.
V9T 4P7

James Morrison
Fisheries & Oceans
3225 Stephenson Pt. Rd.
Nanaimo, B.C.
V8T 1K3

Reinhard Muller
Min. of Forests & Lands
7233 Trans-Canada Hwy.
Box 689
Duncan, B.C.
V9L 3Y1

Brian Murphy
B.C. Forest Prod. Ltd.
Renfrew Division
Honeymoon Bay, B.C.
V0R 1Y0

Fred Newhouse
Min. of Forests & Lands
Bag 5000
Smithers, B.C.
V0J 2N0

Teresa Newsome
Min. of Forests & Lands
540 Borlund St.
Williams Lake, B.C.
V2G 1R8

Gary Norris
Min. of Environ. & Parks
780 Blanshard St.
Victoria, B.C.
V8V 1X5

Ed Oswald
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Katherine Palmer
Larkspur Biol. Consultants
2118 Ferndale Rd.
Victoria, B.C.
V8N 2Y7

Mark Palmer
Box 253
Duncan, B.C.
V9L 3X3

Paul Pashnik
Min. of Forests & Lands
4227-6th Ave.
Port Alberni, B.C.
V9Y 4N1

John Payne
Fisheries & Oceans
Pacific Region
10th Floor
1090 W. Pender St.
Vancouver, B.C.
V6E 2P1

Nicholas Payne
Forest Pest Management Institute
Box 490
Sault Ste. Marie, Ontario
P6A 5M7

John Pellizzon
Balco Industries Ltd.
R.R. #3
Kamloops, B.C.
V2C 5K1

Frank Pendl
Min. of Forests & Lands
4594 Canada Way
Burnaby, B.C.
V5G 4L9

Doug Perdue
Finlay Forest Prod.
Box 250
Mackenzie, B.C.
V0J 2C0

Bill Perry
MacMillan Bloedel Ltd.
Estevan Division
3406-3rd Ave.
Port Alberni, B.C.
V9Y 4E5

Harry Pillar
Greater Victoria Water District
479 Island Hwy.
Victoria, B.C.
V9B 1H7

Gerry Pinkerton
Min. of Forests & Lands
Bag 5000
Smithers, B.C.
V0J 2N0

Les Pinter
MacMillan Bloedel Ltd.
Nanoose, B.C.
V0R 2R0

Doug Pitt
Forest Pest Management Institute
Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Al Planiden
Min. of Trans. & Hwys.
3D-940 Blandshard St.
Victoria, B.C.
V8W 3E6

Vince Poulin
2153 West 46th Ave.
Vancouver, B.C.
V6M 2L2

Raj Prasad
Forest Pest Management Institute
Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Gord Prescott
Weldwood
Box 2179
Vancouver, B.C.
V6B 3V8

Caroline Preston
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Don Purdy
Min. of Forests & Lands
2501-14th Ave.
Vernon, B.C.
V1T 8Z1

Gord Rattray
B.C. Forest Prod.
1050 W. Pender St.
Vancouver, B.C.
V6E 2X3

Gerry Reichenback
Min. of Forests & Lands
4227 Sixth St.
Port Alberni, B.C.
V9Y 4N1

David Reid
B.C. Forest Prod.
Renfrew Division
Honeymoon Bay, B.C.
V0R 1Y0

D. Rekdal
Fisheries & Oceans
Box 10
Port Hardy, B.C.
V0N 2P0

D. Reksten
Min. of Environ. & Parks
2636 Lincoln Rd.
Victoria, B.C.
V8R 6A6

Phil Reynolds
Forest Pest Management Institute
Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Lowell Ritchey
Okanagan Helicopters
34877 Sandon Place
Abbotsford, B.C.
V2S 6B7

James Rodney
Weldwood
Box 2179
Vancouver, B.C.
V6B 3V8

Bill Rugg
Man. Natural Resources
Box 50
20-1st St. S.
Beausejour, Man.
R0E 0C0

Fraser Russell
Min. of Forests & Lands
515 Columbia St.
Kamloops, B.C.
V2C 2T7

Steve Samis
Fisheries & Oceans
1090 W. Pender
Vancouver, B.C.
V6E 2P1

Mel Scott
Min. of Forests & Lands
4595 Canada Way
Burnaby, B.C.
V5G 4L9

Charles Scrivener
Fisheries & Oceans
Pacific Biol. Station
Hammond Bay Rd.
Nanaimo, B.C.
V9R 5K6

Brian Shaw
Skeena Cellulose
Box 3000
Terrace, B.C.
V8G 4C6

Alex Sinclair
FERIC
201-2112 W. Broadway
Vancouver, B.C.
V6K 2C8

Ric Slaco
B.C. Forest Prod. Ltd.
Box 2500
Campbell River, B.C.
V9W 5C5

Geoffrey Smith
1005 Shakespeare Ave.
North Vancouver, B.C.
V7K 1E7

Steve Smyth
Yukon Gov't.
Box 2703
Whitehorse, Yukon
Y1A 2C6

Colin Spence
Fish & Wildlife
540 Borlund St.
Williams Lake, B.C.
V2G 1R8

Dick Stace-Smith
Fed. of B.C. Naturalists
4274 W. 13th Ave.
Vancouver, B.C.
V6R 2T8

John Studens
Canadian Forestry Service
Forest Pest Management Institute
Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Larry Taylor
Monsanto
Box 1159
Delta, B.C.
V4M 3T2

Dean Thompson
Forest Pest Management Institute
Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Glen Thompson
Min. of Forests & Lands
7233 Trans-Canada Hwy.
Box 689
Duncan, B.C.
V9L 3Y1

Jim Thompson
Plum Creek Timber Co, Inc.
Box 51
Roslyn, WA
U.S.A. 98941

Clifford Todd
Fisheries & Oceans
Box 9
Alert Bay, B.C.
V0N 1A0

G. Toft
Environment Canada
Water Survey of Canada
Rm 502-1001 W. Pender St.
V6E 2M9

Derek Tripp
F.F.I.P.
Site T 1, R.R. #1
Nanaimo, B.C.

Tony Trofymo
Pacific Forestry Centre
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Keith Tudor
CIP Inc.
8067 E. Saanich Rd.
Saanichton, B.C.
VOS 1MO

Rod Tysdal
MacMillan Bloedel Ltd.
301-4400 Marine Dr.
Powell River, B.C.
V8A 2K1

Bob Udell
Champion Forest Prod.
P.O. Bag 8000
Hinton, Alta.
TOE 1BO

Ralph Urban
MacMillan Bloedel Ltd.
65 Front St.
Nanaimo, B.C.
V9R 5H9

Ed Vernon
B.C. Wildlife Federation
1-128 Michigan St.
Victoria, B.C.
V8V 1R1

Sylvia von Schuckmann
Min. of Environ. & Parks
780 Blanshard St.
Victoria, B.C.
V8V 1X5

Ron Wallace
Vancouver Water Resources
G.V.R.D.
4330 Kingsway
Burnaby, B.C.
V5H 4G8

Mark Walmsley
Westland Resource Group
1035 A Pandora Ave.
Victoria, B.C.
V8V 3P6

Mike Wan
Environment Canada
Capilano 100- Park Royal
West Vancouver, B.C.
V7T 1A2

Andy Wheatley
Comp. 28
R.R. #1 Pine Tree Pl.
Powell River, B.C.

Roger Whitehead
Canadian Forestry Service
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Charles Wiesner
Research & Prod. Council-N.B.
Fredericton, N.B.

Dave Wilford
Min. of Forests & Lands
Bag 5000
Smithers, B.C.
VOJ 2NO

Ian Williams
Fisheries & Oceans
Pacific Biol. Station
Hammond Bay Rd.
Nanaimo, B.C.
V9R 5K6

C.D. Willson
Min. of Forests & Lands
Box 215
Hazelton, B.C.
V0J 1Y0

Doug Wilson
Environment Canada
Capilano 100- Park Royal South
West Vancouver, B.C.
V7T 1A2

Dave Winston
Canadian Forestry Service
Pacific Forestry Centre
506 W. Burnside Rd.
Victoria, B.C.
V8Z 1M5

Jim Young
Min. of Environ. & Parks
Fish & Wildlife
540 Borlund St.
Williams Lake, B.C.
V2G 1R8